BRNO UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering
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# BACHELOR'S THESIS

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# BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

## FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
FAKULTA ELEKTROTECHNIKY
A KOMUNIKAČNÍCH TECHNOLOGIÍ

## DEPARTMENT OF FOREIGN LANGUAGES
ÚSTAV JAZYKŮ


# RENEWABLE ENERGY SOURCES FROM OCEANS
OBNOVITELNÉ ZDROJE ENERGIE Z OCEÁNŮ

**BACHELOR'S THESIS**
BAKALÁŘSKÁ PRÁCE


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VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ
FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ

# Bakalářská práce

bakalářský studijní obor **Angličtina v elektrotechnice a informatice**

Ústav jazyků

***Studentka:*** Mahulena Krišková ***ID:*** 195237

***Ročník:*** 3 ***Akademický rok:*** 2018/19

**NÁZEV TÉMATU:**

## Obnovitelné zdroje energie z oceánů

**POKYNY PRO VYPRACOVÁNÍ:**

Proveďte rešerši dostupné literatury, identifikujte obnovitelné zdroje energie z oceánů. Prezentujte výsledky rešerše vč. kladů a záporů jednotlivých zdrojů a úrovně jejich využití v současnosti. Přidejte výhled do budoucna a zhodnoťte výsledky v závěru.

**DOPORUČENÁ LITERATURA:**

Multon B. 2013, Marine Renewable Energy Handbook, John Wiley & Sons, Inc., Print ISBN:9781848213326 |Online ISBN:9781118603185

Greaves D., Iglesian G., 2018, Wave and Tidal Energy, Wiley & Sons Ltd., Print ISBN:9781119014447, Online ISBN:9781119014492, DOI:10.1002/9781119014492

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***Vedoucí práce:*** Mgr. Pavel Sedláček

***Konzultant:***

**doc. PhDr. Milena Krhutová, Ph.D.**
*předseda oborové rady*

# Abstrakt

Obnovitelné zdroje jsou v dnešní době velmi diskutované téma především kvůli vyvstávajícím problémům v rámci ekologie a úspory energií. I přes nejvíce zastoupenou část v této oblasti vodními, větrnými a solárními elektrárnami, se tato práce zabývá méně vyvinutou formou čerpání energie pomocí obnovitelných zdrojů, a tím jsou energie z oceánů. Příbojové a přílivové technologie jsou dvěma základními možnostmi, jak efektivně získat určité množství energie. V úvodu jsou popsány jednotlivé možnosti obnovitelných zdrojů a jejich zastoupení v rámci produkce elektřiny. Především jsem se však zabývala jednotlivými typy elektráren a na jakých principech fungují. Dále jsou zde sepsány hlavní dopady na životní prostředí a projekty, které se zabývají inovací oceánských technologií. Cílem práce bylo sestavit rešerši týkající se obnovitelných zdrojů z oceánů tak, aby obsahovala základní dostupné poznatky. Výsledkem je shromáždění informací o využívaných metodách v oblasti oceánské energie, spolu s nejvýznamnějšími elektrárnami světa.



# Klíčová slova

Obnovitelné zdroje, energie z oceánů, elektrárny, přílivová energie, energie z příbojových vln, životní prostředí, rešerše obnovitelných zdrojů z oceánů



# Abstract

Renewable resources are nowadays a serious topic in terms of ecology and energy savings. The dominant producers of clean energy are hydro, wind and solar power plants, however, this paper deals with a less covered type and that is the ocean energy. The efficient harness of energy using ocean power can be distinguished into a wave and tidal technologies. However, this paper covers the background of renewable resources and their worldwide production of electricity, as well as the function of wave and tidal power plants. Moreover, the attention is given the impacts on environment and future innovations in ocean technologies.  The aim of this paper was to conduct a research and describe the basis of the renewable sources from oceans. The result is a summarization of information about wave and tidal converters in order to increase the awareness of this form of utilization of ocean energy.

## Keywords

Renewable resources, wave technologies, wave converters, tidal technologies, tidal power plants, environmental impacts, research into renewable energy resources from ocean

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## Prohlášení autora o původnosti díla

*„Prohlašuji, že svou bakalářskou práci na téma Obnovitelné* zdroje *energie z oceánů jsem vypracoval samostatně pod vedením vedoucí/ho bakalářské práce s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.*

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.V Brně dne: …………………………

Mahulena Krišková, podpis

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I would like to sincerely thank Mgr. Pavel Sedláček for supervising my project and I would like to thank him for the help and advice he gave me when I was writing this Bachelor’s thesis.

# Contents

# 1. Introduction

Impacts of climate changes, the increase in reliance on fossil fuels and the increase in the price of energies are some of the reasons why the demand for renewable energies is growing rapidly. In order to fully understand the sources of energy, it has to be defined what qualifies as sustainable energy to codify and distinguish between renewable and sustainable resources. This paper will review the research conducted on the fundamentals of ocean energies, such as wave, tidal and thermal energy, together with the technologies that are essential in the whole process of energy harnessing. Then, the focus was given to the primary environmental impacts, because it necessary to be acknowledged with the advantages as well as disadvantages of renewable sources, and possible future projects, innovations in this field.

Renewable resources are able to naturally replenished partially or completely with time, or even by recycling of materials and they are widely available. Renewables can be considered as harmless to the environment with a minimal impact on the surroundings – they are inexhaustible and clean. However, the term *sustainable* is wider and contains "*the effectiveness of providing energy in a way that it could become a significant energy resource without compromising the ability of future generations to meet their needs*" (Lemaire, 2010).

The global consumption of non-renewable resources results in ecologically unsustainable consumption. To properly understand this meaning, it is necessary to define what the term ecological sustainability means: "*Ecological sustainability* means that, based on a long-term perspective, we conserve the productivity of the waters, the soil and the ecosystem, and reduce our impact on the natural environment and people's health to a level that the natural environment and humanity can handle" (Löf, 2018).

Ocean energy is one of the renewables that plays a less significant role in global resources. Most of the projects are still in the process of demonstration, yet it does not mean that it has no potential at all. Around 70% of the Earth's surface is covered by oceans that provide a vast amount of ocean power in the form of waves and tides. Only some of the seashores are eligible to convert ocean energy into electricity.

According to a World Energy Resources Marine Energy 2016 report published by World Energy Council (Network of leaders and practitioners promoting an affordable, stable and environmentally sensitive energy system for the greatest benefit of all), it was estimated that around 0.5 GW of ocean energy is provided to the public, and most of its production stems from tidal range (“Marine World Energy Resources 2016”, 2016).

## 2. Characteristics of renewable resources

Generating power from nature's sources has been always an attractive research for many centuries. The idea of converting energy from the Sun, rivers, or wind, is not new, however, as there is the increase of negative effects of fossil fuels and the possibility of its extinction, people are becoming/have become more interested in renewables. Gradually, human civilization developed and improved its knowledge of how to use solar, wind, water energy and other renewable resources, which are additionally described below.

Solar energy is a source that exploits energy from the Sun. Light and heat might be harnessed using technologies such as photovoltaics, solar heating or concentrated solar power. According to the first sources, solar energy was originally used to heat water as early as in the 18$^{th}$ century. However, producing electricity from solar energy remained undiscovered until Albert Einstein proposed an explanation for the photoelectric effect in the early 1900s. Two types of solar power exist – photovoltaic (further PV), which concentrates sunlight and converts it into heat, thermal that produces electricity directly without moving parts ("Solar Energy", 2016).

According to statistics published in a 2017 REN21's (**R**enewable **E**nergy Policy **N**etwork for the **21**st Century is a global renewable energy policy multi-stakeholder network that connects a wide range of key actors, whose goal is to facilitate knowledge exchange, policy development and joint action towards a rapid global transition to renewable energy) report, the investments in solar PV (photovoltaic) energy were the highest than from any other generation of energy, especially in China, India, Japan, and the United States. The number of installed solar PV in 2017 exceeded the net capacity additions in fossil fuel and nuclear power combined. As stated by the researchers of REN21, the worldwide capacity (power that can be potentially used) of this energy in 2017 was approximately 402 GW (Aberg, Adib, et al., 2018).

Traditionally, it is known that the usage of wind energy has been there for thousands of years – people employed the sail to navigate their ships or operated windmills in order to pump water and grind grain (Rinkesh, 2018). With improved technologies, current wind farms could be constructed out of many individual turbines, mostly located onshore.

Further, the total wind power capacity grew in 2017 up to a total number of 539 GW (including offshore and onshore wind power) (Aberg, Adib, at el., 2018, p. 23). The largest onshore wind farm called Gansu is situated in China with the current capacity of 8 GW ("Gansu Wind Farm (China)", 2015) and expected capacity of 20 000 MW by 2020. In contrast, the largest offshore farm called Walney is located in the Irish Sea with a total capacity of 1026 MW (Vaughan, 2018).

Other type of renewable source, geothermal energy is, in general, the heat from the center of the Earth. This energy may be used for example for district heating in the form of hot springs, but mostly serves as a source for electricity generation. Although the ability to be sustainable and renewable, it requires the necessity to be monitored in case of local depletion of wells or air pollution with carbon dioxide, hydrogen sulfide, and methane, since they can contribute to global warming ("Geothermal Energy", 2018). The Geyser, in California, is the largest group of geothermal power plants (22) in the world with installed capacity of

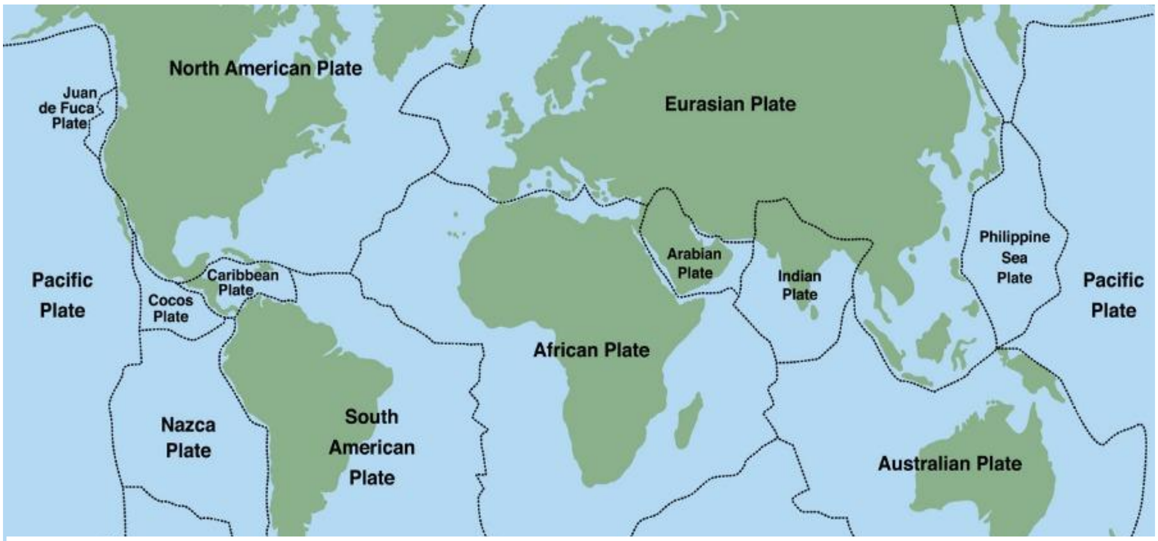



**Figure 1.** Tectonics plates.
(Retrieved from: http://egyptcareers.info/ )

1517 MW ("The Geysers Geothermal Field, California", 2012). Substantially, the location of geothermal power plants depends on plate tectonics boundaries (Figure 1) that create a great option to build them for instance in Japan, Italy, Philippines, the United States, New Zealand, and Mexico.

The total number of the global production of geothermal energy was reported to be 12.8 GW in 2017 (Aberg, Adib, et al., 2018 p. 22).

Another renewable resource, water energy, or hydroelectric power, includes power from rivers, lakes and ocean energy. It was the Romans or Chinese during the Han Dynasty, who started to exploit the tide energy and, subsequently, they began to build tide mills, which are very similar to today's tide power stations.

However, the changes in new technologies were not as recognizable until the Industrial Revolution. Due to the Industrial Revolution in the eighteenth century, people started to be more dependent on oil and coal, but with time, the reserves of these resources are limited. Sørensen (1991) showed that in the 1950s people realized that the question of renewable resources has become more serious and that it is necessary to find solutions regarding sustainable energy system. In the twenty-first century, the topic of renewable energies is debatable as never. Renewables persist to gain global progress, although it depends on a specific region.

Based on the data REN21 from 2016, renewables accounted for approximately 18.2% of total final energy consumption (TFEC), which is about 2.195 GW. Hydropower leads the generation with 3.7%, followed by thermal energy and biofuels (Figure 2).

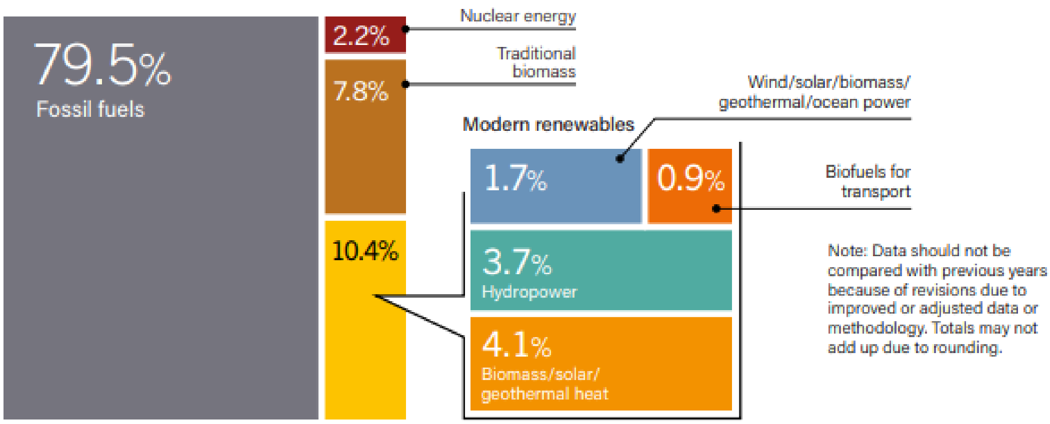



**Figure 2**. Estimated renewable share of total final energy consumption, 2016. (Retrieved from: http://www.ren21.net/ )

# 3. Wave energy technology

There could be two possible definitions of waves – theoretical and technical.

“All waves begin as disturbances, and ocean waves form as the result of a disturbing force. A rock thrown into a still pond, for example, creates a disturbance that generates waves radiating out in all directions. Ocean waves are caused by a similar transfer of energy to the surface of the ocean” (Trujillo & Thurman, 2017, p. 245).

"Wave power is defined by the flow of energy through a vertical surface perpendicular to the direction of its propagation. It could, therefore, be expressed in $W.m^{-1}$” (Multon, 2012, p. 338).

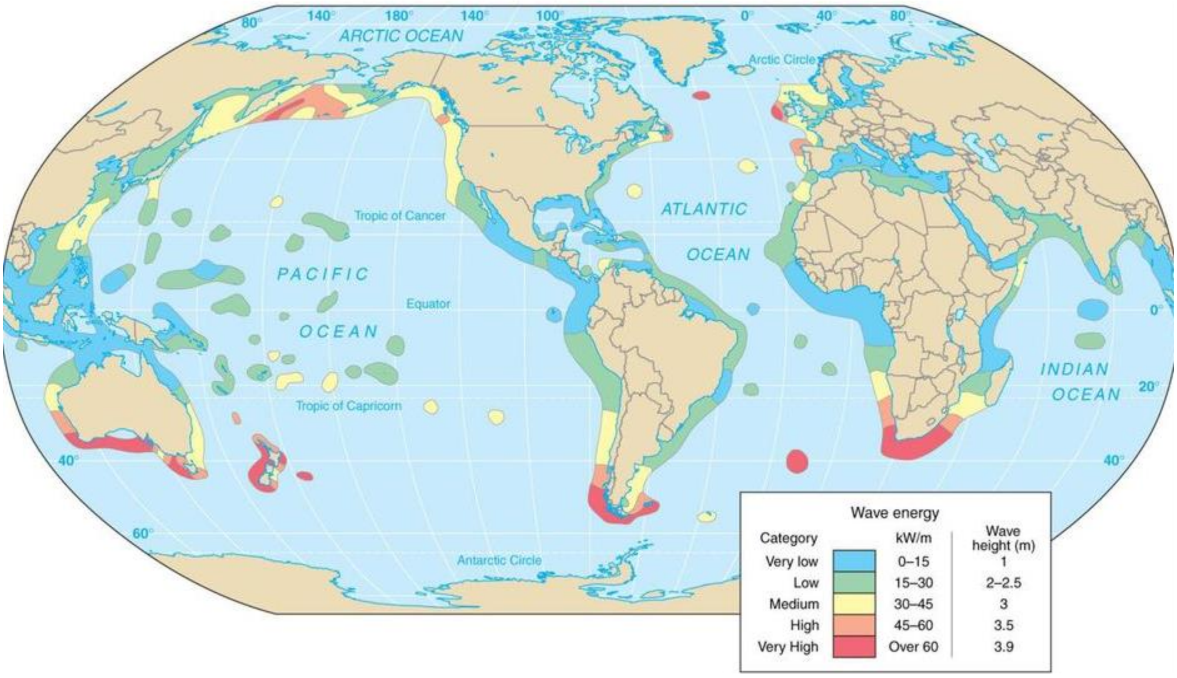



**Figure 3.** The most frequent occurrence of wave power plants. (Retrieved from: https://slideplayer.com)

Waves could be created by blowing of the wind across the ocean, movement of fluids with different density, movement of the large area of seafloor, or they can be even induced by humans (waves created by ships). The size of the waves depends on the wind speed, its duration, and the distance of water over which it blows. The physical parameters of waves are height and length, thus, the waves carrier kinetic energy which can be harnessed by wave energy devices. However, the harness efficiency of ocean waves is the main problem in further development due to the unpredictability of waves contrary to tides, and on frequent occasions, they can be very powerful and excite damage to machines. As the actual power of a given wave cannot be predicted, the system is unable to guarantee a stable supply of power. Moreover, the impact on the environment might be the key problem regarding ocean energy. Survey such as conducted by EU project Aqua-RET (“Wave”, 2012) have shown that with increasing latitudes greater than 40° north or south increases wave energy and thus, the best areas for wave resources occur where strong winds have traveled over long distances with almost no energy loss (wave energy near shores decreases due to friction with the seabed and places far from shores will have the greatest energy). Such places are for example in Western Australia (Perth, Portland), in the United States (Oregon, Hawaii), Portugal (north of Porto), or the United Kingdom (north coast of Cornwall) (Figure 3). In general, out of all renewable resources, ocean energy offers the highest energy density.

The benefits of wave energy in comparison with other renewables might be characterized by highest energy density, predictability, and ability to satisfy electricity demand changes.

## 3.1. Wave energy converters and power plants

Efficient wave capturing has impacts on the design of converters because they have to be able to withstand wave energy. This leads to high expenses and poses difficult engineering challenges. Additionally, up to 95% of the energy in a wave is located between the water surface and one-quarter of a wavelength below it.

WECs (Wave Energy Converter) characterize devices capturing the power of waves and transforming it into electricity. WECs may be categorized according to directional characteristics, working principle, and location (Figure 4).

| Principal Location | Directional Characteristic | | |
|---|---|---|---|
| | Point Absorber | Terminator | Attenuator |
| Shoreline | | OWC, OTD | |
| Nearshore | WAB | OWC, OTD, WAB | WAB |
| Offshore | WAB | OWC, OTD, WAB | WAB |

**Figure 4.** Possible operating principles for the location and directional characteristics. (Retrieved from: http://www.renewablegreenenergypower.com)

Drawing on an extensive range of sources, the authors Drew, Plummer and Sahinkay (2016) set out the ways in which there are three distinct zones:

1. Offshore – considered as the most profitable location since the energy of waves here is the largest. However, the distance from land is associated with the large costs of the maintenance and construction difficulties. Converters built offshore need to be designed to survive extreme conditions.

2. Nearshore – devices installed a few hundred meters from the shore in a depth of 10 to 25 meters. They are often attached to the seabed.

3. Onshore – these devices have the advantage of being fixed to the land. They can be easily maintained due to an accessible position, but the energy of waves is lower and also the available free land can be a problem (environmental problem). The disadvantage is the high possibility of being damaged by wave power. In the end, a small-scale study by Goldman (2018) reaches conclusion that choosing the position depends on the budget availability and the requirements or restriction set by project owners.

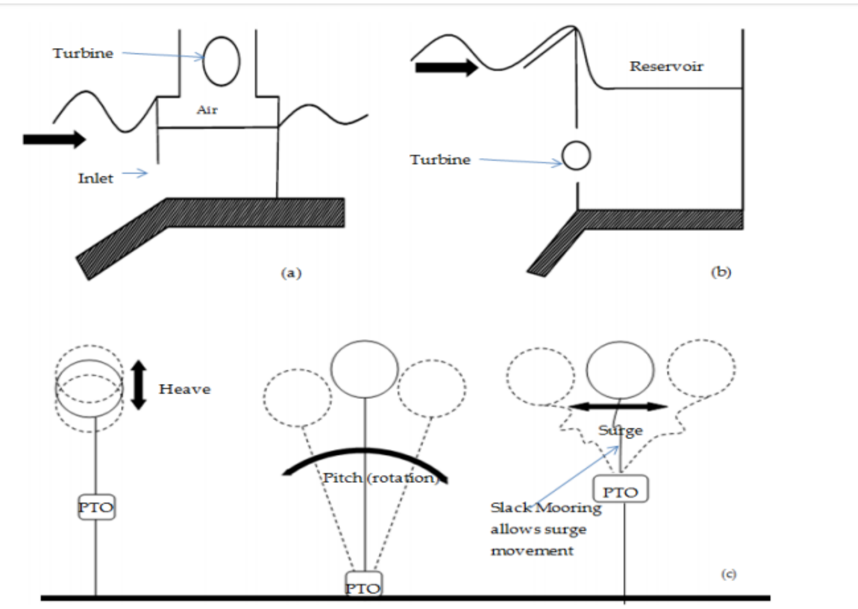



**Figure 5.** Division of three Wave Energy Converters: (a) oscillating water column, (b) overtopping devices, (c) oscillating bodies. (Retrieved from http://www.mdpi.com)

Moreover, designs of WECs are in permanent development, but they can be divided into three main groups: Point absorber, terminator, and attenuator. Attenuators, e. g. Pelamis, lie parallel to the direction of incoming waves. Their motion can be described as 'riding' the waves because they float on the surface and capture energy as the waves move. Point absorbers (e. g. WaveBob) are devices symmetrical about the vertical axis. Drew, Plummer, and Sahinkaya, (2016) identified that they are smaller in terms of the incoming wavelength (wave direction is not important), and currently, they are able to heave up and down on the surface, or even submerged under the surface. Terminators are perpendicular to the direction of wave and they reflect the wave power. These devices have one part greater than the rest of the device and greater than the incoming wavelength.

Lastly, working principles of the WECs could be divided into three areas: oscillating water column (OWC), overtopping devices (OTD) and oscillating bodies (Figure 5).

### 3.1.2. OWC technology

This system is thought to be one of the most popular wave energy technologies for converters and presents two main advantages – a simple working principle and low maintenance cost (relative to other WECs). Although, Multon (2012, p. 349) highlights that the disadvantage could be that the waves possess less power due to wave breaking.

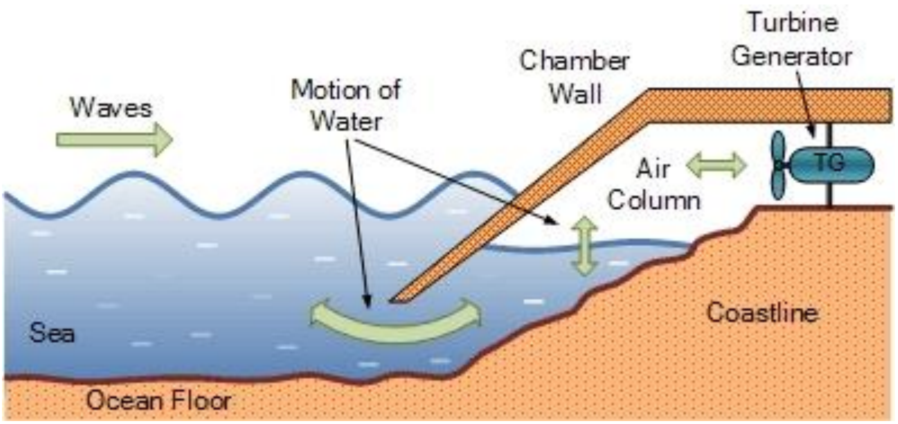



**Figure 6.** A simple scheme of working principle of Oscillating Water Column converter. (Retrieved from: http://www.earthsci.org)

In a review of wave energy converter technology, Drew, Plummer, and Sahinkaya, (2016) identify characteristics of oscillating water column (OWC). This device consists of a partially submerged chamber with an opening exposed to the wave action and turbine. As waves approach the device it causes the water column inside the chamber to oscillate, which enables the water column to act as a piston - the air is firstly pressed within the chamber and then escapes through air turbine. These turbines are designed so that their direction of rotation is independent of the direction of the air flow. The alternating air flows are then converted into electricity. Air is primarily utilized as the working fluid because of the advantage of increasing the slow velocities of waves to the high air flow rate (Figure 6).

OWC may be situated offshore or onshore. Offshore OWC (e. g. Oceanlinx) is a floating device located in deep water, where the power of waves is higher than near the coast - spar buoy is a great example of offshore OWC (it is not sensitive to wave direction) discussed in a paper of Aderinto & Li (2018, p. 5). Wave motions combine the water column motion to determine the output of the device.

On the other hand, onshore OWC stays fixed to the coast in shallow water, and their performance is affected by tidal friction, and most of the wave energy is lost through bottom friction as the depth decreases. One of the advantages of onshore converters compared to the offshore would be that mooring lines are not required since they operate in a safer sea environment. This increases their survivability, maintenance and with electricity generation and coastal protection, they have a dual purpose. These advantages are mentioned in a research of Greaves & Iglesias (2018, p. 99)

The first commercial OWC wave power plant, LIMPET 500 (Figure 7), was built in 2000 and is situated on a small island of Islay on the west coast of Scotland. LIMPET is built of bi-steel, a high resistance material of steel and concrete, and operates with two Wells turbines according to Multon (2012, p. 351).

Design of turbines could be related to the wave frequency and amplitude. Most popular air turbines are Wells turbines (Figure 8) that possess the ability to rotate in the same direction independently on the airflow direction yet their operation has low efficiency (approximately 60%), and they produce high noise.

**Figure 7.** Picture of OWC power plant LIMPET 500. (Retrieved from: https://www.researchgate.net/ )

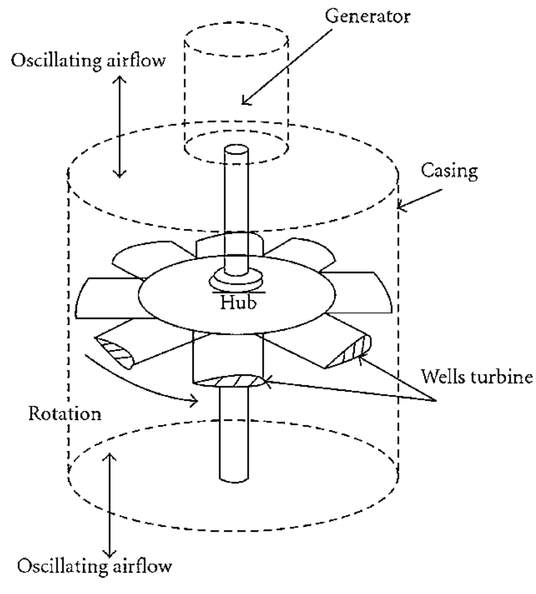



**Figure 8.** Wells turbine. (Retrieved from: https://www.researchgate.net/ )

### 3.1.3. Overtopping devices

Overtopping device captures and concentrates incoming waves in a reservoir above the surface and then lets the waves break on a slope to fill a basin. Their working principle is examined in a study of Multon (2012, p. 347) as well as in a study of Aderinto et al. (2018, p. 7). The water is later released back to the ocean through low-head turbines connected to electrical generators. The reservoir of energy that can be used to ensure the smoothing of the produced power is the advantage of OTD. On the other hand, the system includes a startup threshold – when the incoming waves do not possess enough power to break over the ramp, no energy is produced. This is the main disadvantage of OTD.

Overtopping devices are designed for both onshore and offshore locations. An example of an overtopping device based on the coast is TAPCHAN (TAPered CHANnel) built in 1985 in Norway (Figure 9). Tapchan allowed the incoming wave to increase its height as the channel narrowed towards the reservoir end (place of concentration of propagating waves). However, Multon (2012, p. 347) pints out that this device stopped functioning and was damaged due to a powerful storm in 1991.

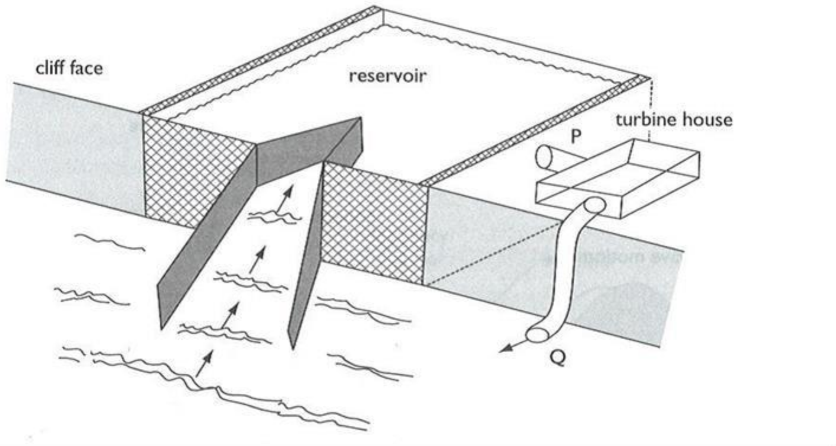



**Figure 9.** Overtopping device TAPCHAN. (Retrieved from: https://www.researchgate.net)

Under the most developed OTD device counts offshore Wave Dragon (WD) in Denmark (Figure 10). Its structure is described by Aderinto & Li (2018, p. 7) as it proceeds with ideas from Tapchan and creates a floating device with two wave curved reflectors on concentrator arms, which enables to concentrate the incoming waves towards the reservoir. Inside the basin are located low-headed turbines (more turbines increase the output energy depending on the available flow rate), which convert the hydraulic head in the reservoir into electricity. WD is unique due to its one-step conversion system – conversion of wave energy directly through the water turbines.

Unlike other WEC technologies, overtopping devices may be constructed very largely due to independence on resonance with the waves. Greaves & Iglesias (2018, p. 105) claim that they only need to focus on controlling and stabilizing the floating structure to optimize power output.

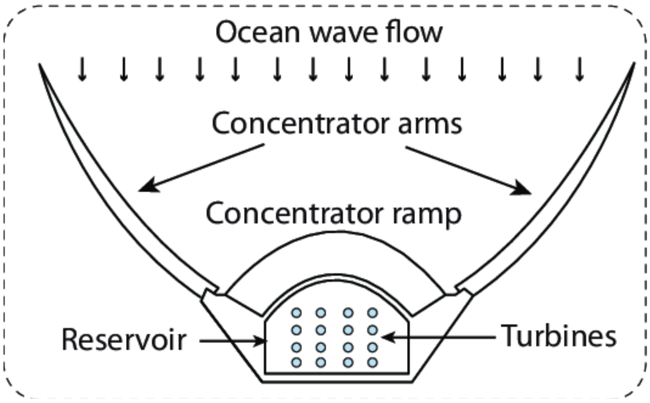



**Figure 10.** Scheme of Wave Dragon (WD). (Retrieved from: www.researchgate.net)

### 3.1.4. Oscillating bodies

In Multon's (2012, p.354) review, these devices are working on a principle of oscillating body move according to the motion of ocean waves that can be mainly heaved or mainly pitched. In contrast to the other types of technologies, oscillating bodies divides into submerged or floating devices that can be further categorized according to system that involves single or multiple oscillators, system using pitch (floating or anchored), system combining heave and pitch or system combining heave and yaw.

Heaving system can be fully submerged with an oscillating upper part, and the bottom part fixed to the seabed. Under the simplest example of the oscillating body comes oscillator attached to the seabed – heaving buoy – where the buoy moves relatively to a fixed frame of reference. The motion between moving and fixed part drives the turbine. PowerBuoy (Figure 11) (Greaves & Iglesias, 2018, p. 106) comes under a categorization of two-body self-referencing WECs with oscillating parts that move relative to one another. These parts might be powered by the hydraulic circuit with PTO (power take-off = transfers the mechanical power of the engine over to another part of the equipment), which is situated between the reaction and float plate. AquaBuoy (Greaves & Iglesias, 2018, p. 106) is an example of floating multibody that heavens devices. In these multibody oscillating bodies, the energy is produced from the motion of two connected parts that oscillates unsynchronized.

Size of body plays an important role in deciding whether a single heaving body and submerged system are able to be installed onshore. However, due to a capturing of lower energy in the heaving mode, they are more suitable to be placed offshore.

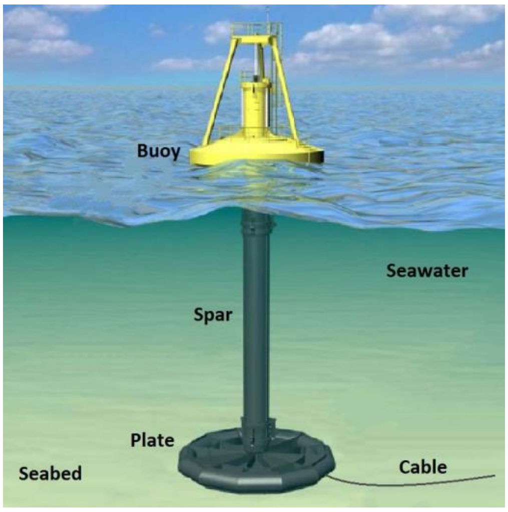



**Figure 11.** PowerBuoy. (Retrieved from: https://www.researchgate.net/ )

### 3.1.4.a. Attenuator (Pelamis)

A typical example of the oscillating body was a Pelamis power plant (Figure 12). Pelamis worked on a principle of attenuator converters and was located a few kilometers off the northwest Agucadoura coast in Portugal (opened in 2008). It was able to generate 2.25 MW. However, two months after the opening of the farm had to be closed down because of financial difficulties. The second project was held in Orkney, Scotland, for Scottish Power Renewables, with the production of 750 kW (shut down in 2014 due to financial difficulties) (Blum, 2009). Moreover, the third wave station with 5 MW was constructed for the Cornwall Wave Hub in the UK ("Pelamis Wave Power", 2015).

In addition, attenuators are considered as a series of long floating structures linked together in a cylindrical shape that are parallel to the wave direction. They are flexible and can last the differing heights of waves on the open sea and adapt to them. The average depth for attenuators is 50-60 meters, where is the highest potential for large swell waves. The semiimmersed floating segments are connected with hinged joints to generate power as the waves are moving across.

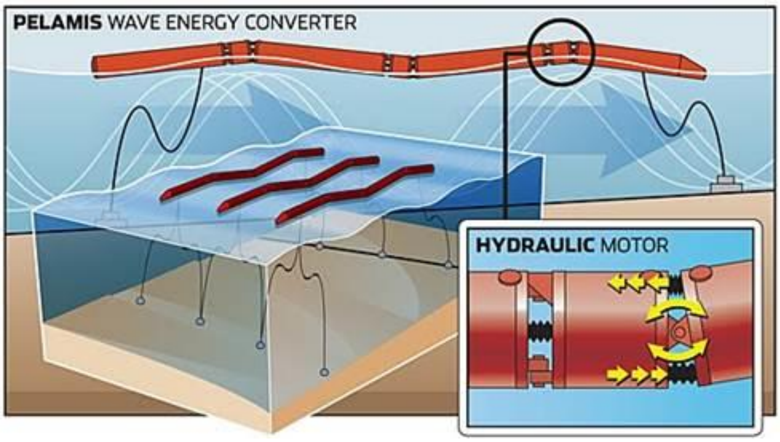



**Figure 12.** Pelamis Wave Energy Converter. (Retrieved from: http://potomacstewards.com)

## 3.2. Conclusion

In this chapter there have been described the basis of wave energy – how are the waves formed, what are possible ways of harnessing energy from this type of renewable source, as well as the primary energy converters used at present in various number power plants. From the available data is known that the most promising location for wave power plants is between 40°- 60° latitude, whereas the position offshore, onshore, or nearshore should not have any significant effect. Europe represents one of the suitable options for various types of wave power plant thanks to a large number of sea areas (mostly the eastern Atlantic), other location could be Japan or India. There have been presented three types of wave converters (WECs): OWC, OTD and oscillating bodies.

Most of the projects are in a development phase, however, only a few of them are commercially used due to a necessary funding for technological progress. Further development is highly requested mostly because the potential for this type of energy conversion shows its advantages, such as reliability, predictability, being environmentally friendly (harnessing does not produce harmful forms of gases, or pollution).

# 4. Tidal energy

Tidal energy is considered as another form of ocean energy that converts its potential into electricity. The base of power harnessing depends on a proper understanding of tides and their working principle. In general, tides are generated by forces imposed on Earth, which are caused by both gravity and motion among Earth, the Sun and the Moon. Multon (2012, p. 188) describes tides by their period (the height between consecutive high and low tides) and range (time between two high and low tides) and provide kinetic (tidal current) and potential energy (tidal range).

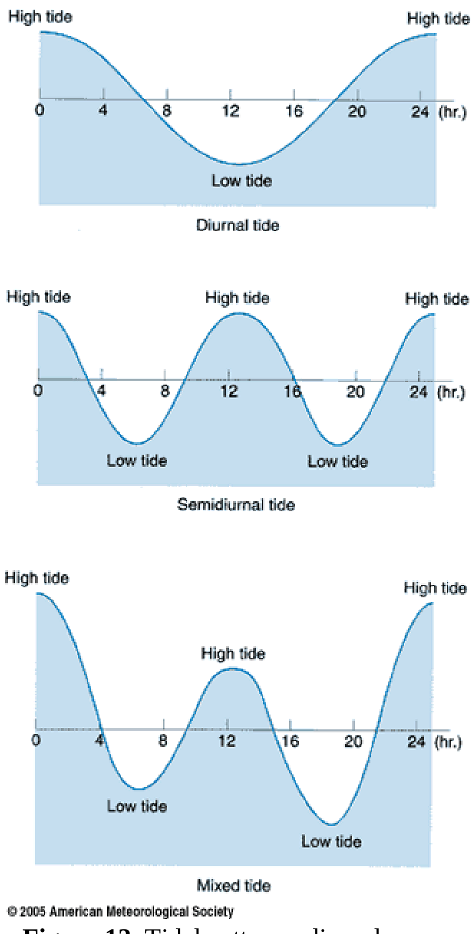



**Figure 13**. Tidal patterns: diurnal, semidiurnal and mixed pattern. (Retrieved from: http://oceanmotion.org)

However, shapes, sizes, and depths of ocean basins differs, which establishes three tidal patterns: diurnal, semidiurnal and mixed pattern (Figure 13). In their study, Trujillo & Thurman (2017, p. 292) identified both of them. Diurnal tidal pattern (typical for shallow islands, e. g. the Gulf of Mexico) is characterized by one high tide and one low tide each lunar day (The rotation period of the moon on its axis equal to the sidereal month of about $27^{1}/_{3}$ days). Semidiurnal tides are defined by two high and low tides on each lunar day in the period of 12 hours and 25 minutes, where the heights of both tides are approximately the same. The highest frequency of semidiurnal tides occurs along the Atlantic coast of the United States. The third pattern, mixed tides, combines both diurnal and semidiurnal tides. The heights of successive high/low tides are significantly dissimilar, and these kinds of tides are commonly found along the Pacific coast of North America.

As the major advantage of tidal energy, stated by Aqua-RET ("Tidal Energy: Technology Brief", 2014, p. 22), can be considered the capability of being highly predictable in cycles. Although its operation is not expensive, the further innovations in technologies regarding tidal power suffered from relatively high cost.

## 4.1. History of tidal energy

In history, people were using tides as a source of power. They were able to use it for driving machines and in the 12th century, the water-energy was used for spinning of water wheels in mills in Europe. In the eighteenth century these two parts of the world started to use hydropower as a source, but since the tidal power was rather expensive, the availability was limited. The first patent for wave energy conversion, developed by Messrs Girard in 1799, was not the right stimulation for using this kind of resource power since the oil and coal were the most affordable and available ones.

The milestone in ocean energy was induced by the first tidal power station the La Rance Tidal Power Station in France. As noted by EDF Group ("Tidal Power: EDF a Precursor", 2018), this power station was built in 1966 and is still operating (producing 240 MW, which estimates around 500 GWh/year). Before Sihwa Lake Tidal Power Station in South Korea, La Rance was the most significant one as regards the output power. A small tidal barrage was put in service in 1984 in Canada's Bay of Fundy, which supposed to demonstrate a turbine invented by Escher-Wyss of Switzerland. It is the only significant barrage on the continent.

In the 1980s, the interest in ocean energy decreased because of low oil cost, and in the 1990s, the price of oil increased again and, subsequently, the demand for alternative sources of energy emerged. Most of the projects regarding ocean energy are not widely developed as yet, but it has the potential to be one of the main sources of renewable energy. Ocean energy is a sustainable resource and can efficiently operate under difficult conditions.

In a total of 12 TW produced from alternative resources, wave energy can go from 1 to 10 TW (Trujillo & Thurman, 2017, p. 273).

### 4.1.1. Tidal range technologies

This power generation can be described as following: “A difference in vertical height of the water level between its highest and lowest point, and tidal range generation extracts energy by harnessing the potential energy which is available through the difference in water height” (Greaves & Iglesias, 2018, p. 129). In other words, this process harnesses the potential energy created by the vertical difference between ebb tide and flood tide. The working principle is always the same – filling the basin, holding the water and producing of the power.

Two types of range system are used: barrage and lagoon.

#### 4.1.1.a. Tidal barrages

Waters and Aggidis (2016, p. 6) summarize that the barrage (dam) is a structure built across the bay or estuary (the wide part of a river at the place where it joins the sea) together with installed turbines along its length, sluice gates, breakwater, and ship locks. With incoming and outcoming tides, the barrage creates a head difference on one side, and as soon as the head difference reaches the turbines, sluice gates are able to open which enables the water to pass through the turbines (Figure 14).

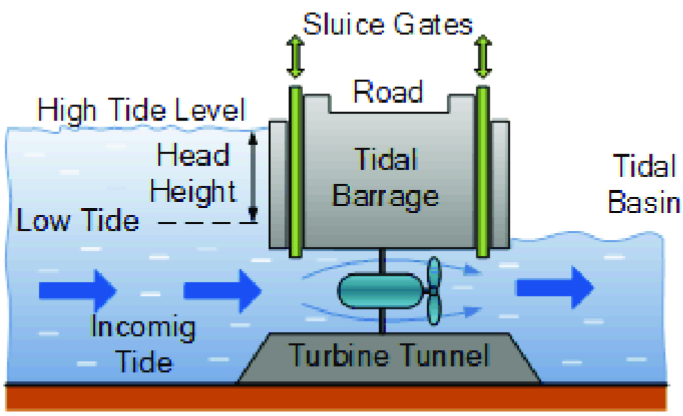



**Figure 14.** The simple working principle of Tidal Barrage.
(Retrieved from: https://www.researchgate.net/ )

There are two systems on which can the barrage operate, which are presented by Etemadi at al. (2011, p. 4). The first is a single-basin system that consists of one basin and the dam. Moreover, they can operate on three principles: flood generation, ebb generation, and dual generation.

- Flood generation's method captures the energy on the flood tide. The sluice gates and turbines are closed during the flood tide until the head difference between the basin and sea reaches the minimum of hydrostatic head of the turbines and moves across the dam. After that, the turbine gates are opened, and the water is able to flow through them to the basin. Tidal power plant working on the flood generation system is, for instance, Sihwa Tidal Power Plant in South Korea. However, the capacity and electric production are limited, and as regards the ecological disadvantage, the water level inside is kept at a low level for a long time.

- Ebb generation operates as the opposite principle of the flood generation. The basin is filled during the flood through the sluice gates, and once the tide reaches its maximum, the sluice gates are closed with trapped water inside of the basin. The gates are opened again when the sea level outside falls enough for the turbines to operate. The Annapolis Royal Generating Station in Canada is an example.

- Dual generation, or two-way generation, employs both flow and ebb techniques and considers as the most complicated one. The turbines need to be optimized in both directions which results in their complexity. At first, the sluice gates are closed until the adequate head difference between the basin and sea. When this condition is fulfilled, the gates are opened, and the water is able to flow through the turbines creating power. The gates are closed again when the minimum head difference is achieved and opened once more allowing the water to flow back through turbines generating energy.

Similarly, Waters and Aggidis's study (2016, p. 6) note that the second type deals with double-basin barrages that are standard single-basin barrages with the installed second basin. In fact, the delivering of electricity is adjustable due to the same working principle of the main basin as in the case of the usual ebb generation basin. As the tide flows back to the sea, the water is pumped and stored in the second basin. Double-basin barrage usage allows delaying the tidal movement at the peak of energy periods. However, installed low-head turbines are considered inefficient and also the construction costs of the extra length of barrages restrict the further development.

### 4.1.1.b. Tidal lagoons

Unlike the typical barrage, lagoon system (Figure 15) encloses to the coastline with a high tidal range behind a breakwater and does not block the river or estuary. The onshore lagoons consist of a dam-like wall that forms a horseshoe shape, and the land finishes the circle, whereas the offshore lagoon's dam forms a complete circle. Conversely, Waters and Aggidis (2016, p. 6) reported no significant difference in the working principle between the tidal barrages and lagoons – he lagoon captures a large amount of water behind the structure which is subsequently released to drive turbines (turbines are bi-directional – they can generate power from incoming or outcoming tides) and produce electricity.

Although the size of lagoons is relatively smaller than barrages, the resulting production of output power increases (the Severn Estuary lagoons offer more than 40% available energy compared to the barrages) ("Severn Estuary Tidal Energy from Non-barrage Options", 2007).

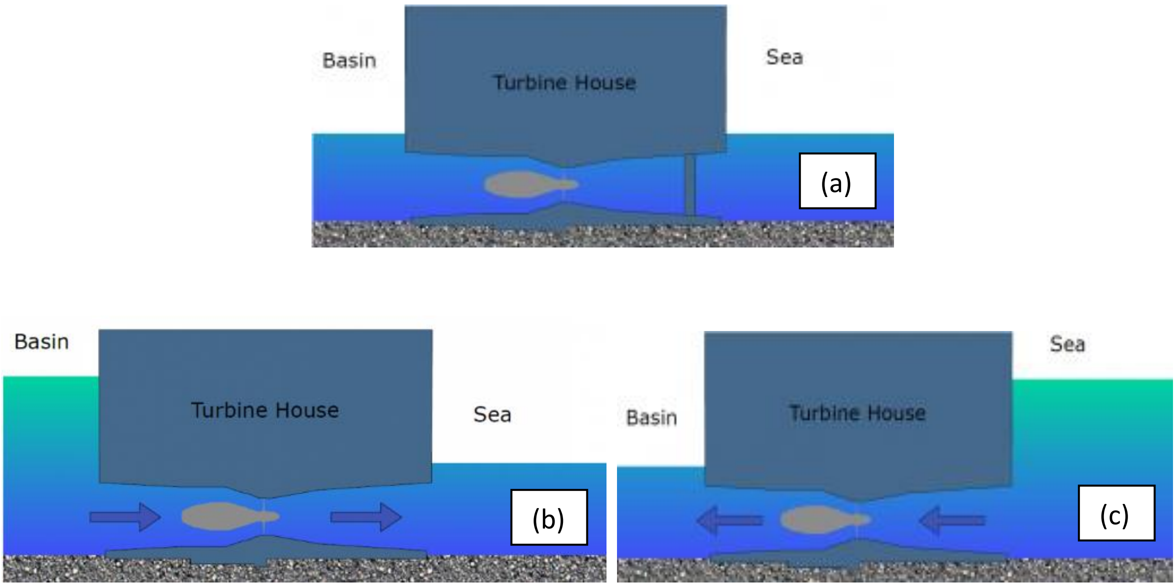



**Figure 15** Holding period at high or low water (a). Generating on the ebb tide (b). Generating on the flood tide (c). (Retrieved from: http://www.tidallagoonpower.com/)

### 4.1.2. Tidal stream technologies

Tidal stream, or tidal current, converts the kinetic energy into the resulting generated power and works as the wind turbines beneath the surface, where are fixed to the seabed. The only difference, highlighted by research of Greaves & Iglesias (2018, p. 132-133), consists in flowing of the water currents across the turbines motor – it does not require the storage of water. Although the tidal stream turbines produce more structural loading when compared to the air driven turbines, the blades require a high degree of robustness since they are fully submerged under the water. There might be high design criteria due to possible material corrosion from salt or possible blade cavitation.

The turbines can be distinguished into two main parts ("Tidal Energy: Technology Brief", 2014):

- Horizontal/vertical-axis and enclosed turbines – in case of these turbines, the blades are positioned perpendicular or parallel to the direction of the flow of the water. The conversion of power involves a turbine rotor (converts the energy of the current), gearbox (converts the low rotational speed to the wanted speed of the generator shaft) and generator (converts the shaft energy to electric power). As regards the enclosed turbines, the stream is here concentrated so that the flow and power from the turbines increases (Figure 16, 17).
- Reciprocating devices – turbines used in these devices are called hydrofoils (from the shape of airplane wings) which allow the up and down motion as the tidal stream flows on one of the sides of the blade. This leads to the movement conversion into the rotation to drive the rotating shaft (Figure 17).

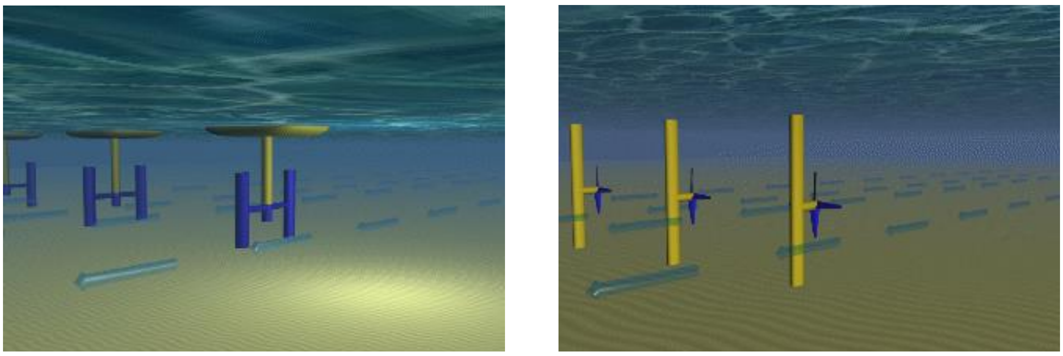
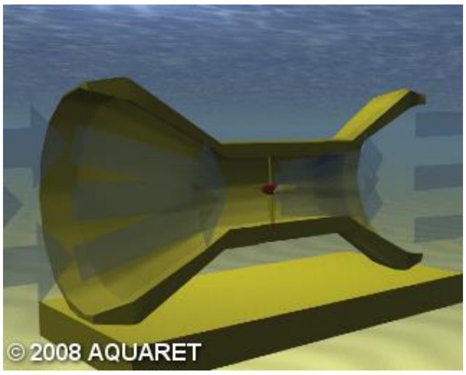


**Figure 16.** Horizontal turbines. (left), vertical turbines (right). (Retrieved from: http://www.emec.org.uk)

All tidal stream structures need support to keep them in place and withstand the conditions at sea. There exist three possibilities of installation based on data of Aqua-RET ("Tidal Stream: Construction and Installation (Level 2)", 2012): gravity structure, piled structure and floating structure (Figure 18). Gravity structures are made of massive steel on concrete and attached to the bed. Other options that enable the structures to be pinned to the seabed are piled structures. The connection can be made either by one or more steel/concrete piles. Floating structures allow the installation in deep water locations due to the turbine is mounted to the barge (anchored to the seabed using ropes or chains).



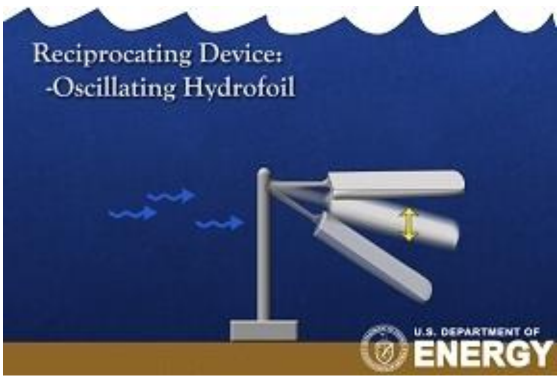




**Figure 18** Enclosed turbines (left), reciprocating devices (right). (Retrieved from: http://www.emec.org.uk )

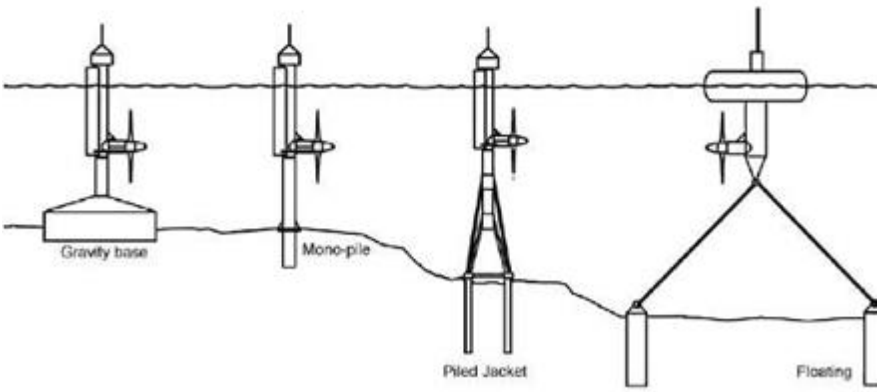



**Figure 17** Support structure concepts. (Retrieved from: http://www.aquaret.com)

### 4.1.3. Tidal power plants

International Renewable Energy Agency (IREN) (“Tidal Energy: Technology Brief”, 2014, p. 19) conducted research and defined that most of the tidal energy devices are located onshore, but there is a possibility to build them in various depths and distances from the coastline. The Bay of Fundy in Canada is the most protentional place for the highest tides in the world – up to 17 meters in amplitude. Other places with maximum amplitudes from 10 to 13 meters can be found on the coast of Argentina, the UK, Brazil, north-western Australia, France, South Korea or Alaska (Figure 19). For the construction of any tidal power plant, there exist criteria that must be followed: the possibility of building of a large reservoir, the minimum average amplitude of 5 meters, and sufficient water depth for installation of the turbines.

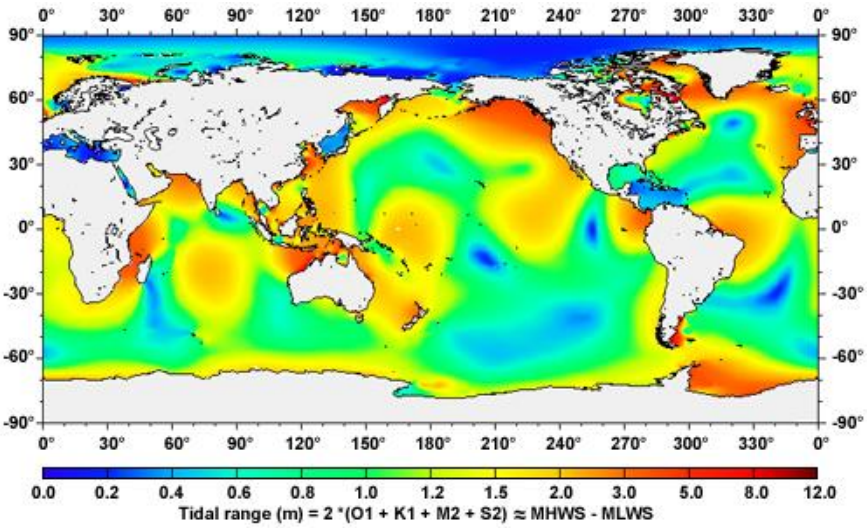



**Figure 19.** Global Tidal Range. (Retrieved from: https://wegc203116.uni-graz.at/)

#### 4.1.3.a. The Rance Tidal Power Plant (France)

Multon (2012) points out the most significant tidal power plants. The first tidal power plant that took advantage of tides and their power was built at the Rance River in France (Figure 20). After five years of construction, the Rance power plant was opened in 1966 and for many years remained the largest one until Sihwa power plant (2011).

The situation was chosen due to the highest and largest tidal range in France – the average tidal range can reach 8 meters between high and low tide (spring tide is able to reach almost 14 meters). With the total length of 750 meters, the reservoir can hold 184 million m$^3$. The barrage consists of 24 individual bulb electricity turbines (nominal power 10MW) that give the total installed capacity of 240MW (the annual generation of 500GWh/year) (“Tidal giants – the world’s five biggest tidal power plants”, 2014).

The working principle is based on a bidirectional cycle, and the bulbs are also used as pumps for the increase of head difference.

**Figure 20.** The Rance Tidal Power Plant in France. (Retrieved from: https://www.renewableenergyworld.com/)

### 4.1.3.b. Lake Sihwa Tidal Power Plant (South Korea)

Kwater, South Korean governmental agency for comprehensive water resources, participated in designing multiple hydro power plants, one of them is Lake Sihwa Tidal Power Plant (“Sihwa Lake Tidal Power Plant”, 2018). Its construction was started in 2004 and completed in 2011, since when the Sihwa Lake Tidal Power Station (Figure 22) is considered to be the largest operating tidal power station. The power station is built on the artificial lake, which was first projected to provide land for the metropolitan area and to hold irrigation water for agriculture means. However, the water quality deteriorated due to nearby industries and was no longer useful. In order to reduce the pollution by adding fresh water into the lake with each tidal cycle, a tidal barrage was constructed.

In general, Multon (2012) claims that the western coast of South Korea (Figure 21) offers a great condition for tidal power generation (the tidal ranges reach up to 9 meters). As regards the Sihwa power plant, the average tidal range reaches 7 meters and is located in the Gyeonggi Bay. Sihwa operates only on water flowing from the sea towards the reservoir through 8 sluice gates and ten bulb groups (installed capacity of 245MW) and produces approximately 552GWh annually. In a case study of Sihwa Lake Tidal Power Plant, Kim Y. H. declares: „The 552.7 GWh of electricity generated from Sihwa tidal power plant is equivalent to 862,000 barrels of oil, or 315,000 tons of $CO_2$ – the amount produced by 100,000 cars produce annually. "(Kim, 2018).

The effort to further development is a key factor for Korea government, followed by the Korea Water Resources Corporation (Kwater) vision to include integrated field surveys, plant optimization processes, modelling works, and enhance the water quality via seawater circulation. The Sihwa power plant is known for environmentally friendly approach towards being opened to the public that includes building of a tidal power culture center in the tidal lake area.

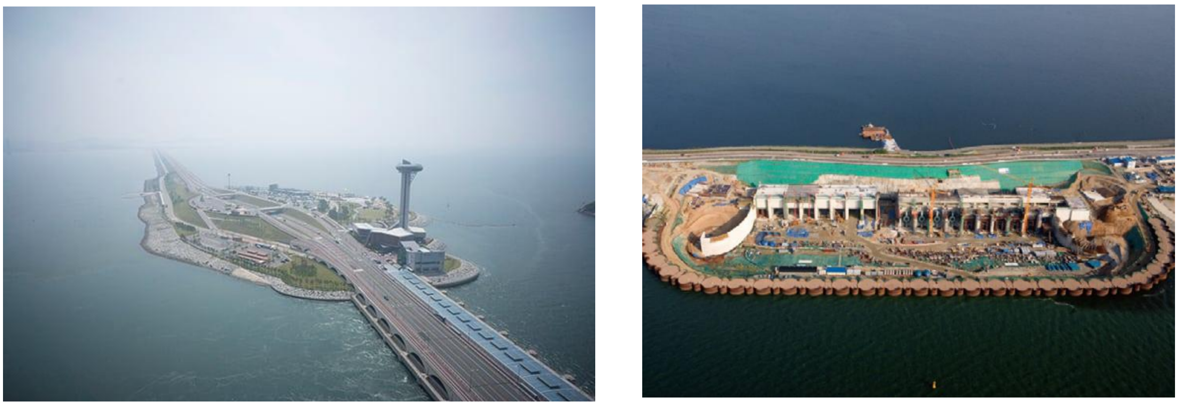


**Figure 22.** Sihwa Power Plant in South Korea. (Retrieved from: https://cdn.powermag.com)

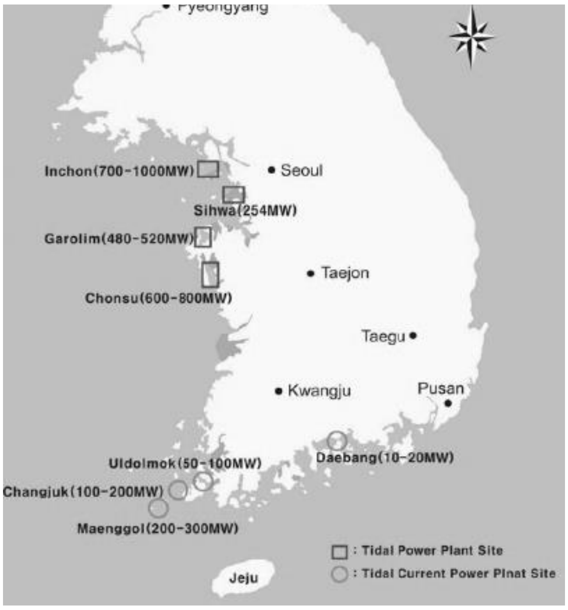



**Figure 21.** Picture of the most significant tidal power plants on the western coast of South Korea. (Retrieved from: Greaves, D., & Iglesias, G. (2018). Wave and tidal energy )

### 4.1.3.c. Annapolis (Canada)

The Annapolis Royal Generating Station (Figure 23) is the first and only modern tidal power plant in North America operating since 1984. The location for this power plant was chosen due to the highest tide range in the world – 16 meters. The power is generated only during the ebb tide only and produces 20MW (annual output 50GWh) using a single turbine, mentioned in "Annapolis Tidal Station" (2018).

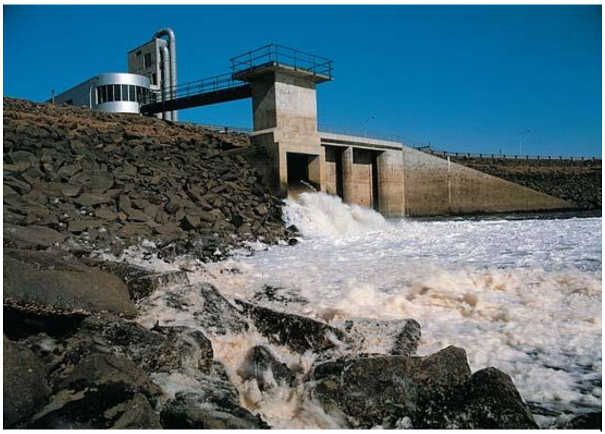


**Figure 23.** Tidal Power Plant Annapolis in Canada.
(Retrieved from: https://tethys.pnnl.gov/ )

### 4.1.3.d. MeyGen Tidal Energy Project (the UK)

As noted by Mearns (2018), the construction of MeyGen tidal power plant was devided into three phases where only the first, phase 1a, is completed and phase 1b and 1c are in the deployment. The location was chosen according to the high speed of current in the Pentland Firth, Scotland (up to 5 m/s). Phase 1a consists of 1.5 MW turbines and reached the required installed capacity of 6 MW (in 2016). The phase 1b, which is currently (2019) under development, will likely to bring 4 more turbines and phase 1c should be composed of further 49 turbines increaing the installed capacity to 86 MW. This power plant is constructed to be tidal tream type that harnesses power with the help of wind power – turbines are situated under the water surface in order to harness the energy of naturally strong tidal flows. Such kind of power plant offers minimal damage to surrounding environment due to unnecessity to build sea wall.

## 4.2. Conclusion

In reviewing the literature, tidal energy is assumed to be a significant part in ocean energy, especially in certatin locations (for example The Bay of Fundy in Canada). The chapter dedicated to tidal energy includes not only the general summary of technological possibilites, but also the decription of tidal power plants. In particular, the Sihwa Lake Tidal Power Station in South Korea that is at present the largest of its kind (with installed capacity of 245 MW).

There were mentioned two primary systems of tidal technolgies – tidal stream and tidal rannge, which are additionally divided into tidal barrages and lagoons. Although the tidal range system requires the storage of water, stream devices are most of the time deteched to the ocean/sea bottom as the water flows across the turbine motors. The main challenge for technological development was stated to be the increase of turbine efficiency as they are predetermined to withstand in a harsh evironment.

# 5. Ocean Thermal Energy

Ocean Thermal Energy Conversion (OTEC) technology operates on a principle that can produce electricity by harnessing the distinctive temperature between cold deep ocean water and warm tropical surface waters (thermal gradients). For the OTEC to function properly, the temperature difference is required to range from at least 20°C to ideally 30-40°C (Hossain et al., 2013). Apart from the heat from the core of the Earth, moreover, the solar radiation has to be considered. Figure 24 shows the average solar flux measured on the surface per 24 hours and it can be seen that it is natural to associate hot regions with sunny regions.

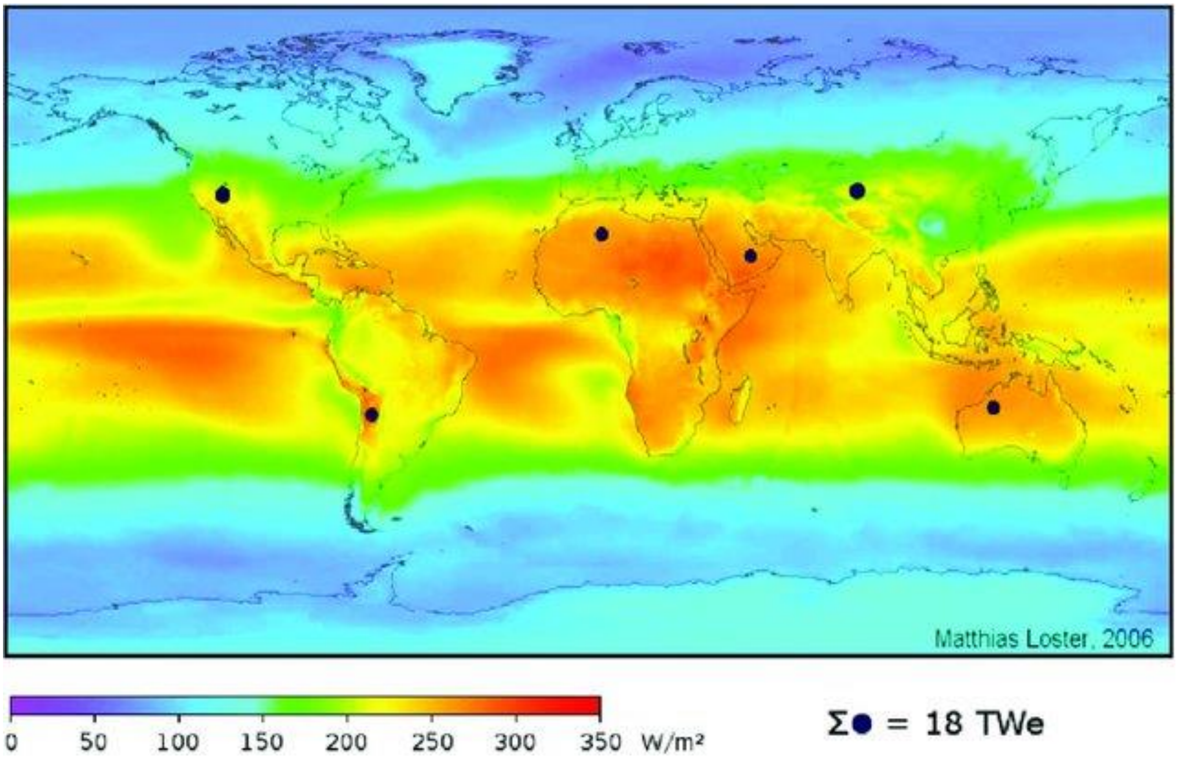



**Figure 24.** Average solar flux on the earth's surface from 1991 to 1933, measured in W/m$^2$. Black points significates annual electricity production of nearly 18 TWh.
(Retrieved from: www.researchgate.net)

Hossain et. al. (2013), moreover, include that when the Gulf Stream, carrying warm surface currents, arrives at relatively high latitudes having colder air, the ocean loses a huge deal of heat. Further, slight exchanges occur as well between the land (ocean) and the atmosphere. All the above-mentioned factors must be considered when dealing with the thermal energy on account of the forces that move the ocean masses.

Ocean masses are generally identifiable bodies of water created in the deep ocean including a thermocline (the transition layer between warmer mixed water at the ocean's surface and cooler deep water below) ("What is a thermocline?", 2018). As a result of rapid decrease of temperature from the mixed upper layer of the ocean to significantly colder deep water in thermocline, the depth and strength of thermocline in the ocean may change depending on the season and year.

In survey of Bralower and Bice (2011) the primary masses of deep ocean are:

- North Atlantic Deep Water (NADW) mass originates in the seas of Norway and Greenland, where the surface is cooled and carries a temperature of 2-3°C. NADW travels down the west side of the North Atlantic Ocean and through the west side of the South Atlantic at an average depth of 2 500 meters (see Figure 25).
- Antarctic Deep Water (AADW) runs beneath the NADW with a temperature of approximately 0°C and at an average depth of 4 000 meters. Considering it the densest and coldest mass of them all, AADW is produced in the Southern Ocean (exactly around the coast of Antarctica and under the Ross sea) (Figure 26).

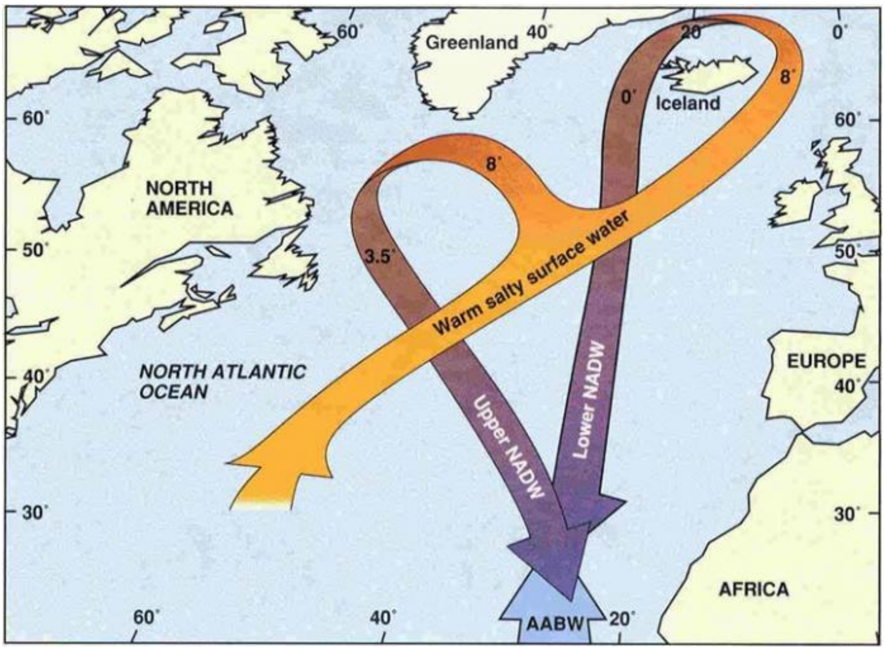



**Figure 25.** Map showing formation of North Atlantic Deep Water in the northen part of the North Atlantic. (Retrieved from: https://www.e-education.psu.edu)

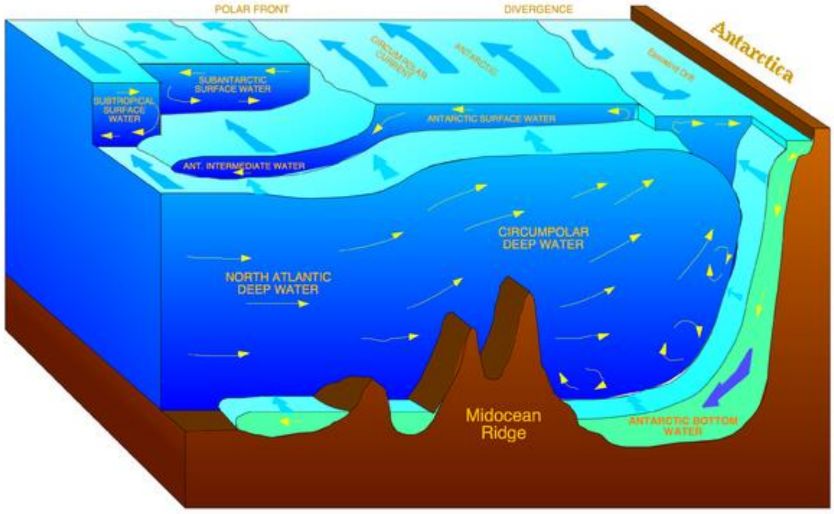



**Figure 26**. The formation of Antarctic Deep Water in the Southern Ocean. (Retrieved from: http://www.wikiwand.com)

Nonetheless, Cenedese and Gordon (2019) are concerned with what moves masses, currents and the overall oceanic circulation is the thermohaline circulation (THC) (Figure 27) that is controlled by the horizontal temperature differences and salinity and is defined by a flow rate. This very slow process takes the vast amounts of seawater from the bottom of the ocean and replaces it with the water from the surface and consecutively replaces the surface water elsewhere with water from deeper parts.

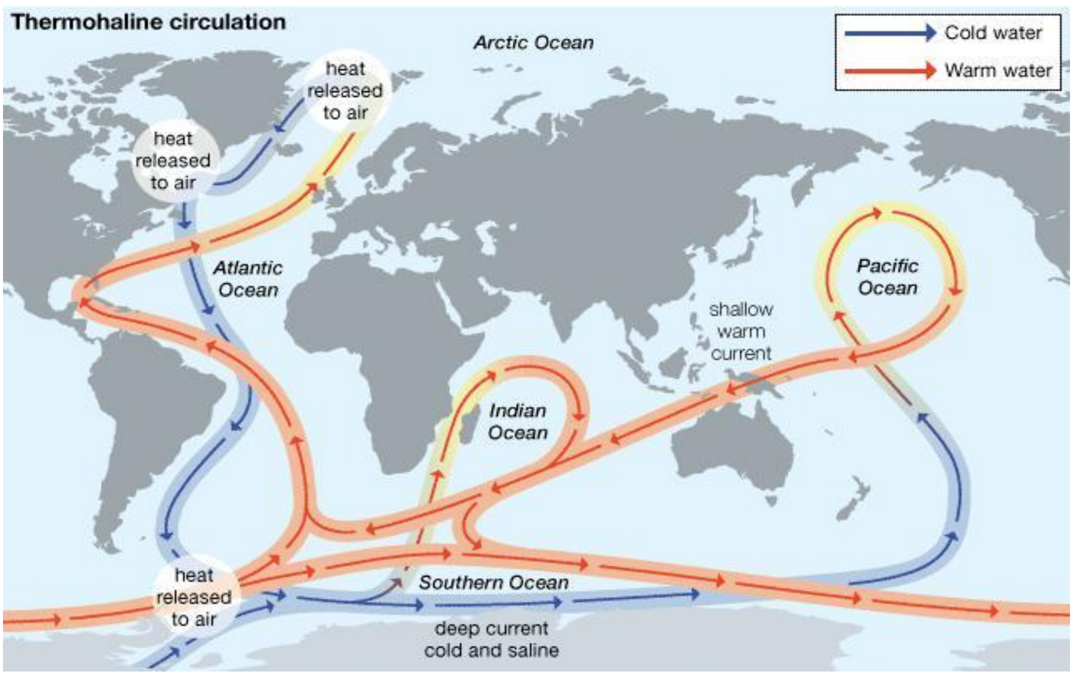



**Figure 27.** Thermohaline circulation. (Retrieved from: https://www.britannica.com)

Acknowledging all the information about masses and currents is crucial in terms of understanding the OTEC functional principle. As a part of renewable resources, most of the electricity that is used comes from heat engines, a system which cycles between two various temperatures – cold deep parts beneath the surface and hot surface of the ocean. Thermal power plants constructed on land might work on a similar principle with only one exception. The heat engine, particularly steam engine or steam turbine, is powered by heating the engine with coal. However, in OTEC no fuel is burned, since the thermal gradient derives itself naturally. The potential consists of providing large quantities of base load energy.

In addition, most of the OTEC systems are, as well as the wave systems, a part of several experimental projects (Hossain et al., 2013) despite the already developed technology. This is due to the lack of operational records required to be eventually commercialized, the lack of consistent funding from government, or the necessity of permission from Environmental Impact Statements (EIS).

The main parts of OTEC are evaporator, condenser, turbine, pump and power generator, and all of them are connected with pipes (including working fluids, for example ammonia).

## 5.1. The thermodynamic cycles and energy conversion systems of thermal energy

Multon (2012) identifies several advantages and disadvantages of the cycles. So far, the main advantage regarding open cycle, as well as hybrid cycle, involves the production of electricity equal to the production of drinking water. In contrast, large amounts of air must be pumped in order to obtain a high vacuum (dissolving gases in the seawater), in addition, the open cycle construction requires a very large turbine, because of the low pressure.

Closed cycle deals primarily with the usage of working fluid; therefore, the initial construction costs are lower due to small turbogenerators (reduced amount of work in terms of volume). However, notable disadvantage is the greater degree of biofouling (the gradual accumulation of waterborne organisms, such as bacteria, on the surfaces of engineering structures in water that contributes to corrosion of the structures and to a decrease in the efficiency of moving parts) (“Definition of biofouling”, 2019) due to double-walled exchangers.

Furthermore, there could be a certain drawback associated with the hybrid cycle – the initial costs are the highest out of all three types.

In general, the OTEC power plants might be considered valuable in biomass due to a production of biofuels, and because of the cold seawater, the OTEC can be possibly used to cool down buildings, according to Multon (2012). However, OTECs could be exploited only in the tropics, since the temperature difference between the bottom and surface is not great enough. The most efficient energy conversion would be 8% for 26°C warm and 4°C cold seawater.

### 5.1.1. Open cycle energy conversion system

Open cycle operates on a warm seawater (approximately 26°C) as a working fluid, where the water is pumped from the surface and further evaporated in a vacuum chamber (very low pressure) to create a steam. Subsequently, the steam expands through low pressure turbine connected to the generated and creates electricity. When leaving the turbine, the steam is condensed by a cold seawater (around 5°C) in a cold-water pipe (Figure 28) (Multon, 2012).

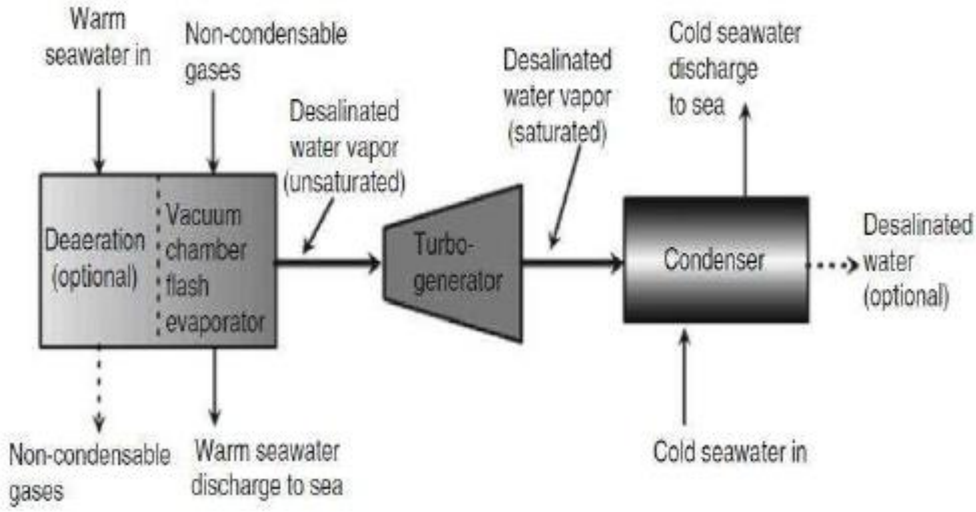



**Figure 28.** Open cycle. (Retrieved from: https://www.researchgate.net/)

### 5.1.2. Closed cycle energy conversion system

Closed cycles may be divided into three main categories on the basis of the utilization of warm and cold sources: Rankine cycle, Kalina cycle and Uehara cycle. However, Hossain et. al. (2013) conclude that Rankine cycle operates on pure and organic mixture of auxiliary fluid, whereas Kalina cycle and Uehara cycle working fluid consists of mixture of ammonia and water.

The selection of the working fluid is crucial, however not all of the criteria can be satisfied, such as its thermal conductivity, the toxicity or explosiveness, impacts on the environment, or its vaporization enthalpy that should be high, and much more.

Multon (2012) lists three types of fluids:

1. Inorganic refrigerants – water, carbon dioxide, ammonia (this fluid has been extensively used for over then century, yet is highly toxic)
2. Hydrocarbons – compounds of hydrogen and carbon only (propane, butane, propylene).
3. Hydrofluorocarbons - chlorofluorocarbons (CFSs) and hydrochlorofluorocarbons (HCFs) are prohibited due to the proven harmfulness to the ozone layer. Hydrofluorocarbons (HFCs), which are currently used, are considered not harmful to the ozone layer, although there has been found an evidence of contribution to the greenhouse effect.

### 5.1.2.a. Rankine cycle

Rankine cycle is described in an university textbook (Mastný, Morávek, Pitron, & Vrána, 2015, 19) as a thermodynamic cycle used not only in thermal power plants, or solar power devices, but found in OTEC as well. The working principle corresponds with the basic closed cycle operation – it needs the fluid to be capable of boiling at ambient temperature when receiving heat form surface warm water in the evaporator. The auxiliary fluid (for example ammonium) is pumped into the evaporator, then vaporized and eventually it rotates the turbine activating power generator, which results in creating electricity. The already processed vapor leaves the turbine and is then condensed by cold deep seawater inside condenser (Figure 29). The process repeats itself continuously in order to produce electricity.

Nevertheless, in Rankine cycle the working fluid does not have to be only ammonium. Having said that, in Organic Rankine Cycle the fluid contains carbon and hydrogen, the opposite one, Rankine cycle without any other indicators uses inorganic fluids (H2O, CO2, ammonia).

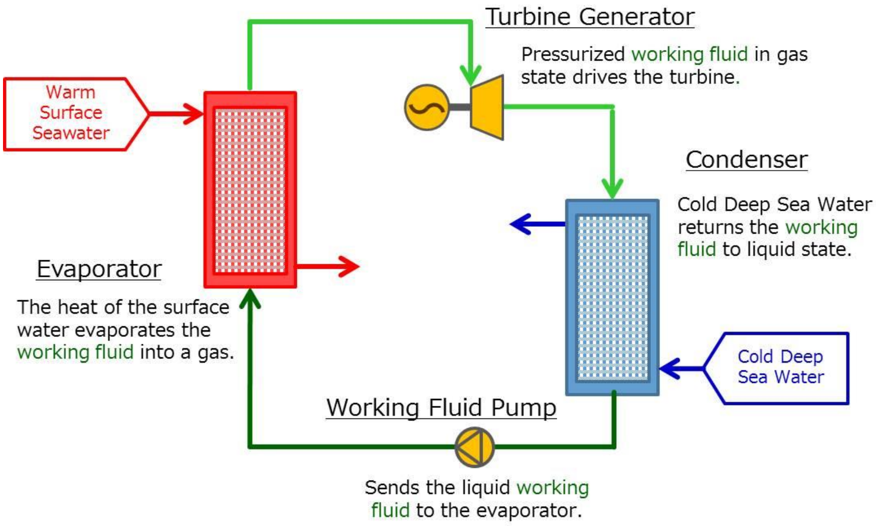



**Figure 29**. Closed cycle; Rankine cycle. (Retrieved from: https://www.researchgate.net/)

### 5.1.3. Hybrid cycle conversion system

Hybrid cycle combines the best features of the closed and the open cycle and its purpose is to produce electricity as well as fresh water, therefore the result offers greater potential. The warm seawater flows to a vacuum chamber where it is evaporated into steam (like in open cycle). The steam vaporizes the auxiliary fluid of a closed cycle and the vaporized fluid rotates the turbine to create electricity. Finally, the steam condensates providing desalinated water.

## 5.2. OTEC Okinawa, Japan

The Okinawa Thermal Power Plant (Figure 30) ("Post-OTEC Seawater Utilization Demonstration Project", 2019) is currently the only continuously operating OTEC since 2013; the maximum capacity can reach up to 100kW a year with coal as the working fuel. In 2017, a project of Post-OTEC Seawater Project – Kumejima Model (1.25 MW) – was constructed in order to integrate larger scale OTEC (power production) and deep seawater use in a system that efficiently utilizes the ocean resources. The installation of pipelines allows deep and surface water to be employed by nearby industries, which results in more fresh water for power generation.

Regarding the future of OTEC Okinawa, based on project conducted by Okinawa company ("Into the Future", 2019) there are being realized several other projects, such as the Power Generation Demonstration Test for measuring the amount of power generation during weather and temperature changes, or the establishment of offshore OTEC in order to reduce the cost of power generation.

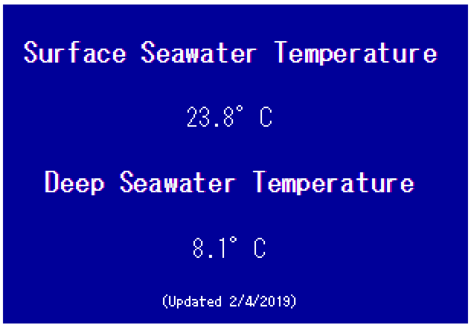



**Figure 30.** The Okinawa Thermal Power Plant pipes (left), The current temperature of seawater in Okinawa, Japan on 4th of February, 2019 (rigt). (Retrieved from: http://otecokinawa.com/en)

## 5.3. OTEC Makai, Hawaii

In their report, the Natural Energy Laboratory of Hawaii Authority (NELHA) reported how OTEC Makai works together with the construction history ("Natural Energy Laboratory of Hawaii Authority 2017 ANNUAL REPORT", 2017). NELHA administrates the Hawaii Ocean Science and Technology Park (HOST Park) in order to provide the islands with green economic development and ocean-based energy since 1974. The OTECs could supply a high degree energy security with minimal gas emissions, and, moreover, support land transportation. The total output may be abundant enough to provide the additional electricity demand.

To effectively use the potential of Hawaii islands, NELHA decided to launch a project with the support of the State of the Hawaii government - the Mini-OTEC Project (1977). This offshore closed-cycle power plant operated on ammonia as a working fluid. Deep seawater was pumped under pressure towards the condenser through a flexible tube. Nevertheless, the possible output of 50 kW was not achieved due to a low turbogenerators and low pumps efficiency. In the end, it was able to reach a production of net power of nearly 20 kW.

Another Hawaii's project, the OTEC-1, was conducted in 1980 with 1 MW of nominal power, however, the design lacked a turbine which led to the usage of this OTEC as a test of the heat exchangers. The operation was withdrawn after a few months of functioning as a result of severe maintenance costs and the necessity of generators to be constantly operated on diesel fuel.

Currently, the first closed-cycle OTEC connected to the US grid since 2015, Makai Ocean Thermal Power Plant is located at the Natural Energy Laboratory of Hawaii Authority in Kailua-Kuna with annual power generation capacity of 100kW a year. The cost of energy supply greatly differs from Okinawa due to the usage of ammonia as the primary working fluid.

## 5.4. Conclusion

OTECs are considered rather new type of possible ocean energy, in comparison to wave or tidal. In this part of the Bachelor's thesis, the main goal was to describe working principle of OTEC technology - in order to function correctly, the difference between deep sea water and the surface is stated not to be less than 20°C, which complies to the location in tropics. The operation could be compared to thermal power plants, however, OTECs heat engine does not burn fuel, instead it uses seawater as a working fluid. In general, conversion system can be divided into three categories – open cycle, hybrid cycle, and closed cycle, which is believed to be the most used one. In particular, Rankin cycle, part of the closed cycle. The significant power plants are enlisted additionally (OTEC Makai in Hawaii or Okinawa in Japan).

# 6. Environmental impacts

The main concern regarding environmental issues such as global warming and climate change increases the demand for more clear sources of energy in many countries. Their interest focuses on the usage of less environmentally damaging resources in order to decrease the level of greenhouse gas emissions that is one of the great challenges of the 21st century. The climate change is defined as "*periodic modification of Earth's climate brought about as a result of changes in the atmosphere as well as interactions between the atmosphere and various other geologic, chemical, biological, and geographic factors within the Earth system*" (Jackson, 2019), and followed by the question whether the climate change is attributed only to human activity or seen as a natural process. It is known that the situation has changed rapidly after the Second World War as there was a huge increase in fossil fuel consumption. Nevertheless, there are other potential environmental changes caused by ocean energy sources.

Several research on environment and its impacts were conducted. In paper *Environmental Impact Assessments for wave energy developments* by Leeney et. al (2014) mention that the environmental effects created by wave and tidal devices are bound to have impact on physical as well as on the biological level – location, construction and maintenance, coastal erosion, fish, noise and visual appearances. The larger-scale commercial array the static device is the higher the risk. Concerning dynamic devices, tidal power plants are likely to have, in general, higher level of risk then wave dynamic power plants. Typically, dynamic devices are rotating, oscillating parts of the power plant that may have further effects on the environment in terms of animals colliding with these moving parts.

Some studies, for example study of Copping et. al. (2016), are concerned with the generation of noise by the vessel traffic in constructions and maintenance, and by the operation of ocean power plants – the most noticeable noise level is derived from pile driving, but it still does not reach the level of noise generation of offshore wind power plants and their full-sized pilings installation. The reason is that most of the ocean devices are attached to the seafloor. Moreover, not only this but the impact on the sound communication and navigation of marine animals might be one of the concerns, since this could affect their behavior for hunting, migration, or avoiding threats. Research about other significant evidences and conclusion is needed in order to avoid present uncertainties.

Additionally, an installation of an ocean power plant may contribute to changes in water flow and circulation as the kinetic energy is extracted from the natural movement causing sediment transport or changing the benthic habitats, which might result in flushing (systematic replacement of water in a bay or estuary as a result of tidal flow) (Cook, 1982). Besides this, data show that the various individual devices are unlikely to have any significant effect on flow change thus far. In the future, the attention should be given to larger devices consisting of more than 100 turbines.

Another potential risk to the ocean environment, mentioned by Copping et. al. (2016), might pose the presence of artificial chemicals. These chemicals are used for coating the exterior parts of devices to prevent them from corroding, and they can eventually become toxic and leak into the water (biocides, anticorrosion materials). Although the effects of chemical are known and studied, the number of ocean power plants is not as high as the number of cargo ships, personal ships, yachts etc. that are producing greater water pollution and might be more harmful to the environment. As a result, the greater risk is associated with oil, fuel and other hazardous substance leakage during installation or maintenance, but these risks are already taken into consideration and are highly researched and understood.

Concerning wave devices, the positive aspect could be its ability to protect coastal stretches from the risk of erosion or flooding due to the prediction of sea level rising; it provides the adaptability to sea level rise. Other aspects might be taking into consideration the location of installation in order to reduce the final effect on fishing or other uses of the sea. On the other side, the installation could have a negative effect in a form of underwater sound from the WECs, which may further harm the marine animals. Additionally, harnessing devices contain power cables, anchors and other non-moving parts, which may also lead to interaction with marine animals and potentially disturb their natural predation. Nevertheless, point absorbers in WECs are not considered to be the risk for marine animals as stated in research of Akar and Akdoğan, (2016).

In terms of tidal power plants, there can occur risks regarding possible changes in the estuary basin (local scouring) or contamination due to the reduced flushing rates leading to increased water quality. Although most of the potential impacts could be considered the same as in the wave devices, tidal devices are more associated with the possible loss of some habitats, such as salt marshes, and damage of the benthic habitats due to change of ocean bottom. There appears to be higher chance in device or turbine collision with marine animals as tidal devices are more frequently designed as static constructions attached directly to the bottom of the ocean then wave devices.

According to a case study of the potential of the Severn Estuary analyzed in *Environmental impacts of tidal power schemes* (Wolf, Walkington, Holt, & Burrows, 2009), which is a place with the highest tidal range in the United Kingdom, the essential impact is the higher chance of flooding due to the increase of tidal amplitude, however, the increase is still not that significant to be seen as harmful. Another data shows that due to the disruption of the bottom by water being less turbid there happens to be a raise in penetration. The solution to this is to use turbines for pumping to enhance head differences prior to electricity generation.

In addition, an example of a positive impact on the surrounding environment might be the Sihwa Tidal Power Plant as it was built mainly with the intention to increase the water quality in the lake. Since its opening, there are data showing improved water quality, reduction of floods, and, subsequently, the increase in the species diversity and in the tidal flat area due to a regular exchange of seawater.

However, there are no definite evidences of how much these devices could harm the surrounding environment, the concentration of available information is limited due to the often very costly research (examples of projects dealing with this research are SOWFIA ("Streamlining of Ocean Wave Farm Impacts Assessment", 2019), ORECCA ("Final Report Summary - ORECCA", 2012)). Other studies of the behavior of marine animals were focused on better understanding of interaction with ocean power plants and the final conclusion suggested that these collisions are rather rare. There is still little evidence regarding significant effects and for that reason further monitoring and collecting of proofs of animal behavior will be required. The final impacts could be compared with offshore wind power plants that are equal, or possibly even higher.

# 7. Visions of the future

As far as the future development is concerned, the key issue lies in project funding and investments to support the emerging technologies, which would introduce more efficient and compatible ocean harnessing devices. The European Commission is one of the main participants in promoting the potential usage of oceans as a significant part of electricity production not only for individual households, but for wider range. The reason is the high concentration of possible locations in Europe for power plants constructions as well as the necessity towards decarbonization. The UK, France and Ireland are currently the leaders in deployment of ocean technologies in the coming years.

Besides this, in comparison with other renewables the cost of ocean devices is higher mainly due to greater technology costs (wave/tidal production €0.25-37/kWh, wind €0.18/kWh) (“Ocean Energy: Action needed to deliver on the potential of ocean energy by 2020 and beyond”, 2014, 12), which eventually leads to uncertainties in technical field and lack of experience. The intention is to reduce these costs via Research and Development programs.

Horizon 2020 (H2020) could be one of the solutions. This project of the European Union research and innovation program is included in the Europe 2020 (research area concentrating on investments in future jobs and growth, safety and environment, strengthening the EU’s global position in technology and research). With funding of nearly €80 for 7 years (2014-2020) (“What is Horizon 2020?”, 2014), the primary purpose was to give an opportunity to the private investment, and to ensure the growth in science in order to improve the public and private cooperation in delivering innovations. Renewable energy solutions are inevitably part of H2020 project, especially, the aim is to focus on reducing initial and operational costs, and increase reliability of the ocean devices, since these are the main reasons why so little has been developed so far. The ocean energy projects are associated with new integrated designs of tidal and wave devices so as to increase their lifetime and resistance. According to a data from *Horizon 2020* (“Horizon 2020”, 2018, 120), in 2019, there should be a complete plan of pre-commercial procurement program for wave energy research and development. At the first stage of preparations, it was stated that it is expected to come up with clearly identified technologies, which would further be tested as prototypes.

With the continuous innovations in ocean technologies, more and more projects receive the attention of public or private companies. In terms of H2020, the EU is trying to meet 10% of the total Europe power demand by 2050. DTOceanPlus (2018-2021) project might be one of the most promising ones with the specialization in designing tools for wave and tidal arrays in the upcoming years. ("About DTOceanplus", 2018)

Moreover, *The Ocean of Tomorrow* was a 2011 EU's proposal for several projects concentrating on ocean-wind energy, rather than the conversion itself, and bringing up three projects: H2OCEAN, MERMAID, TROPOS. For example, H2OCEAN project dealt with electricity generation from wind-wave power on the open sea for hydrogen generation. The aim was to create economically sustainable multi-use platform. Nevertheless, demonstrated in *Ocean Energy: Action needed to deliver on the potential of ocean energy by 2020 and beyond* (2014), all three projects were postponed due to a lack of investments.

Regarding the current projects under H2020, there are currently many including the Italian project IMAGINE that develops the Electromechanical Generator. This device is said to "*be able to convert slow speed alternating linear motion into electricity on the basis of continuous magnet generator."* ("UmbraGroup takes lead in €3.8M wave energy project", 2018) Another funding was given for the development of the MegaRoller project (designed in conjunction with OWCS) ("MegaRoller Project Reaches New Milestone", 2019), which might include 1 MW power take-off under the cooperation of 10 partner companies. The aim of this project is to reduce cost of energy and to produce commercially available wave device.


**Figure 31.** MegaRoller. (Retrieved from: https://marineenergy.biz)

# 8. Conclusion

This Bachelor’s thesis was intended to focus on the main principles of wave and tidal energy processes. The terms regarding *renewable* and *sustainable* were defined and there was provided basic knowledge about the further topic. The aim of this thesis was to acquaint readers with the possibilities of energy converters in terms of wave, tidal energy, and other possible ways of ocean energy harnessing, such as ocean thermal energy or salinity gradient energy. In particular, I searched the literature and described the particular methods since each working principle differs and individual devices can be structured and situated variously – onshore, offshore or nearshore. Further, the maintenance also varies, and thus, every project is created according to specific conditions. The ocean power plants are situated mostly in locations of the highest waves or tides. In this thesis, I selected and listed the most significant of them and demonstrated the locations on enclosed maps.

Wave and tidal energy can provide a sufficient source of energy as well as other alternative sources, although the development of the ocean technologies is still at its beginning. There must be done more research and made more efforts to be able to ensure that renewable energies will provide us with a large amount of accessible and environmentally safe power in the future. The problem with achieving the increase of alternative power plants is the cost-effectiveness, simplicity, and requirement of minimal maintenance. Nevertheless, other important topic is dealt with the environmental impact. The fossil fuel plants might be one of the causes of the global pollution of water, air, soil and subsequently the global warming. Even though the statements about human contribution to global warming are at present widely questioned, so far, there are no confirmed definite data. However, ocean energy also deals with the environmental impacts and is not always environmentally-friendly. The key lies in understanding the necessity of choosing the right development technologies without harming the ocean life.

Although harnessing energy from natural sources has existed longer than the production of energy by using non-renewable sources, the reliance on fossil fuels is still higher in general. The developments of ocean devices started in 1960s (La Rance power plant) and since then the importance of looking for alternative sources of energy has grown rapidly. Not only private companies, but the governments in countries all around the world are focusing on the future potential in renewables. Ocean energy is inevitably a significant part of this wide area and deserves greater attention. So far, not many information is available regarding ocean technology, however, it is only due to a lack of investments into these projects. As soon as the development receives sufficient attention and funding, the hidden potential will be revealed.

In conclusion, it should be stated that the ocean energy is sustainable and able to reduce dependence on fossil fuels as well as the solid and air pollution. Moreover, the predictability and reliability give it the advantage over other types of renewables – solar and wind energy. Tidal and wave energy will be able to fulfill the future potential under these conditions – lowering the initial and installation costs in order to build ocean power plants on larger scale and improving present technologies (e.g. turbines) to increase final efficiency.

# 9. List of references

Greaves, D., & Iglesias, G. (2018). Wave and tidal energy. Hoboken, NJ: Wiley. ISBN: 978-111-9014-447

Mastný, P., Morávek, J., Pitron, J., & Vrána, M. (2015). Fundamentals of Energy Processes and Electricity Generation. FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION BRNO UNIVERSITY OF TECHNOLOGY.

Multon, Bernard (2012). Marine renewable energy handbook. Hoboken, NJ: John Wiley, 2012. ISBN 978-1848213326.

Trujillo, A. P., & Thurman, H. V. (2017). Essentials of Oceanography (Twelfth edition). Boston: Pearson.

## Electronic references

Aberg, E., Adib, R., et al. (2018). ADVANCING THE GLOBAL RENEWABLE ENERGY TRANSITION: Renewables 2018 Global Status Report [Online], 51. Retrieved from http://www.ren21.net/wp-content/uploads/2018/06/GSR_2018_Highlights_final.pdf

About DTOceanplus [Online]. (2018). Retrieved May 19, 2019, from https://www.dtoceanplus.eu/About-DTOceanPlus/Description

Aderinto, T., & Li, H. (2018). Ocean Wave Energy Converters: Status and Challenges. Energies, 11(5). https://www.mdpi.com/1996-1073/11/5/1250

Akar, S., & Akdoğan, D. A. (2016). Environmental and Economic Impacts of Wave Energy [Online]. In *Handbook of Research on Green Economic Development Initiatives and Strategies* (pp. 285-309). IGI Global. https://doi.org/10.4018/978-1-5225-0440-5.ch013

Annapolis Tidal Station [Online]. (2018). In *Tethys*. Retrieved from https://tethys.pnnl.gov/annex-iv-sites/annapolis-tidal-station

Bevilacqua, G., & Zanuttigh, B. (2011). Overtopping Wave Energy Converters: general aspects and stage of development [Online]. Retrieved from https://www.researchgate.net/publication/265630995_Overtopping_Wave_Energy_Converters_general_aspects_and_stage_of_development

Blum, P. (2009). A Setback for Wave Power Technology [Online]. In *The New York Times*. Retrieved from https://www.nytimes.com/2009/03/16/business/global/16iht-renport.html

Bralower, T., & Bice, D. (2011). Major Deep Water Masses [Online]. Retrieved May 19, 2019, from https://www.e-education.psu.edu/earth103/node/847

Cenedese, C., & Gordon, A. L. (2019). Thermohaline circulation [Online]. Retrieved May 19, 2019, from https://www.britannica.com/science/ocean-current#ref1121214

Cook, D. O. (1982). Tidal flushing [Online]. In *Beaches and Coastal Geology* (pp. 819-820). Dordrecht: Kluwer Academic Publishers. https://link.springer.com/referenceworkentry/10.1007%2F0-387-30843-1_463

Copping, A., Sather, N., & , L. (2016). Annex IV 2016 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World [Online]. Retrieved May 19, 2019, from https://tethys.pnnl.gov/publications/state-of-the-science-2016, pp 224

Definition of biofouling [Online]. (2019). Retrieved May 19, 2019, from https://www.merriam-webster.com/dictionary/biofouling

Drew, B., Plummer, A. R., & Sahinkaya, M. N. (2016). A review of wave energy converter technology [Online]. *Proceedings Of The Institution Of Mechanical Engineers, Part A: Journal Of Power And Energy*, *223*(8), 887-902. https://journals.sagepub.com/doi/10.1243/09576509JPE782

Etemadi, A., Emami, Y., AsefAfshar, O., & Emdadi, A. (2011). Electricity Generation by the Tidal Barrages [Online]. *Energy Procedia*, *12*, 928-935. https://www.sciencedirect.com/science/article/pii/S1876610211019485?via%3Dihub

Final Report Summary - ORECCA [Online]. (2012). Retrieved May 19, 2019, from https://cordis.europa.eu/project/rcn/94058/reporting/en

Gansu Wind Farm (China) [Online]. (2015). In . Retrieved from https://www.thewindpower.net/windfarm_en_17492_gansu-wind-farm.php

Geothermal Energy [Online]. (2018). In *Renewable Energy News & Information*. Retrieved from https://www.renewableenergyworld.com/geothermal-energy/tech.html

Goldman, A. (2018). Introduction to Wave Energy Converters, WECs [Online]. *Renewable Green Energy Power*. Retrieved from http://www.renewablegreenenergypower.com/introduction-to-wave-energy-converters-wecs/

Horizon 2020, Work Programme 2018-2020: 10. Secure, clean and efficient energy [Online]. (2018). Retrieved May 19, 2019, from http://ec.europa.eu/research/participants/data/ref/h2020/wp/2018-2020/main/h2020-wp1820-energy_en.pdf

Hossain, A., Azhim, A., Jaafar, A. B., Musa, M. N., Zaki, S. A., & Fazreen, D. N. (2013). Ocean thermal energy conversion: The promise of a clean future [Online]. In *2013 IEEE Conference on Clean Energy and Technology (CEAT)* (pp. 23-26). IEEE. https://www.researchgate.net/publication/259484486_Ocean_Thermal_Energy_Conversion_The_Promise_of_a_Clean_Future

Into the Future [Online]. (2019). Retrieved May 19, 2019, from http://otecokinawa.com/en/Project/Future.html

Jackson, S. T. (2019). Climate change [Online]. Retrieved May 19, 2019, from https://www.britannica.com/science/climate-change

Kim, Y. H. Technology case study: Sihwa Lake tidal power station [Online]. In the International Hydropower Association. Retrieved December 08, 2018, from https://www.hydropower.org/blog/technology-case-study-sihwa-lake-tidal-power-station

Leeney, R. H., Greaves, D., Conley, D., & O'Hagan, A. M. (2014). Environmental Impact Assessments for wave energy developments – Learning from existing activities and informing future research priorities [Online]. In (Vol. 99, pp. 14-22). https://www.sciencedirect.com/science/article/pii/S0964569114001732

Lemaire, X. (2010). Glossary of Terms in Sustainable Energy Regulation [Online], 11. Retrieved from https://www.reeep.org/sites/default/files/Glossary%20of%20Terms%20in%20Sustainable%20Energy%20Regulation.pdf

Löf, R. -M. (2018). Ecological sustainability [Online]. In *the University of Gävle*. Retrieved from https://www.hig.se/Ext/En/University-of-Gavle/About-the-

University/Environmental-Work/What-is-sustainable-development-at-HiG/Ecological-sustainability.html

Marine_World Energy Resources 2016 [Online]. (2016). Retrieved from https://www.worldenergy.org/wp-content/uploads/2017/03/WEResources_Marine_2016.pdf

Mearns, E. (2018). The MeyGen Tidal Stream Power Station: Pentland Firth, Scotland [Online]. Retrieved May 19, 2019, from http://euanmearns.com/the-meygen-tidal-stream-power-station-pentland-firth-scotland/

MegaRoller Project Reaches New Milestone [Online]. (2019). Retrieved May 19, 2019, from https://marineenergy.biz/2019/03/20/megaroller-project-reaches-new-milestone/

Natural Energy Laboratory of Hawaii Authority 2017 ANNUAL REPORT [Online]. (2017). Retrieved May 19, 2019, from https://nelha.hawaii.gov/wp-content/uploads/2018/03/Annual.Report.2017.Final_.Final_.Final_.pdf

Ocean Energy: Action needed to deliver on the potential of ocean energy by 2020 and beyond, 2014 § (2014). Brussels: European Commission. Retrieved from https://ec.europa.eu/maritimeaffairs/sites/maritimeaffairs/files/docs/body/swd_2014_13_en.pdf, 64.

Pelamis Wave Power [Online]. (2015). In *The European Marine Energy Centre LTD*. Retrieved from http://www.emec.org.uk/about-us/wave-clients/pelamis-wave-power/

Post-OTEC Seawater Utilization Demonstration Project [Online]. (2019). Retrieved May 19, 2019, from http://otecokinawa.com/en/Project/PostOTECSeawater.html

Rinkesh. (2018). What is Sustainable Energy? [Online]. In *Conserve Energy Future*. Retrieved from https://www.conserve-energy-future.com/sustainableenergy.php

Sihwa Lake Tidal Power Plant [Online]. (2018). In *K-Water*. Retrieved from http://english.kwater.or.kr/eng/tech/sub01/sub02/patentPage.do?s_mid=1207

Solar Energy [Online]. (2016). In *Alternative Energy Solutions for the 21st Century*. Retrieved from http://www.altenergy.org/renewables/solar.html

Sørensen, B. (1991). A history of renewable energy technology [Online]. *Energy Policy*, *19*(1), 8-12. https://www.sciencedirect.com/science/article/pii/030142159190072V?via%3Dihub

Streamlining of Ocean Wave Farm Impacts Assessment [Online]. (2019). Retrieved May 19, 2019, from https://ec.europa.eu/energy/intelligent/projects/en/projects/sowfia

The Geysers Geothermal Field, California [Online]. (2012). In . Retrieved from https://www.power-technology.com/projects/the-geysers-geothermal-california/

Tidal Energy: Technology Brief [Online]. (2014). In . Retrieved from http://www.irena.org/documentdownloads/publications/tidal_energy_v4_web.pdf

Tidal giants – the world's five biggest tidal power plants [Online]. (2014). In *Power Technology*. Retrieved from https://www.power-technology.com/features/featuretidal-giants-the-worlds-five-biggest-tidal-power-plants-4211218/

Tidal Power: EDF a Precursor [Online]. (2018). In *EDF*. Retrieved from https://www.edf.fr/en/the-edf-group/industrial-provider/renewable-energies/marine-energy/tidal-power

Tidal Stream: Construction and Installation (Level 2) [Online]. (2012). In *Aquaret*. Retrieved from http://www.aquaret.com/index4961.html?option=com_content&view=article&id=119&Itemid=262&lang=en

UmbraGroup takes lead in €3.8M wave energy project [Online]. (2018). Retrieved May 19, 2019, from https://marineenergy.biz/2018/05/31/umbragroup-takes-lead-in-e3-8m-wave-energy-project/

Vaughan, A. (2018). World's largest offshore wind farm opens off Cumbrian coast [Online]. In . Retrieved from https://www.theguardian.com/environment/2018/sep/06/worlds-largest-offshore-windfarm-opens-cumbrian-coast-walney-extension-brexit

Waters, S., & Aggidis, G. (2016). Tidal range technologies and state of the art in review [Online]. *Renewable And Sustainable Energy Reviews*, *59*, 514-529. https://www.sciencedirect.com/science/article/pii/S136403211501730X?via%3Dihub

Wave [Online]. (2012). In *Aquaret*. Retrieved from http://www.aquaret.com/images/stories/aquaret/pdf/chapter4.pdf

What is a thermocline? [Online]. (2018). Retrieved May 19, 2019, from https://oceanservice.noaa.gov/facts/thermocline.html

What is Horizon 2020? [Online]. (2014). Retrieved May 19, 2019, from https://ec.europa.eu/programmes/horizon2020/en/what-horizon-2020

Wolf, J., Walkington, I. A., Holt, J., & Burrows, R. (2009). Environmental impacts of tidal power schemes [Online]. In *Proceedings of the Institution of Civil Engineers - Maritime Engineering* (Vol. 162, pp. 165-177). https://www.icevirtuallibrary.com/doi/10.1680/maen.2009.162.4.165

# 10. List of figures